# A FUNCTION GENERATOR
# FOR A TIME SEQUENTIAL ANALOGUE COMPUTER

by

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B.Sc., Dunelm, 1951

A THESIS SUBMITTED IN PARTIAL FULFILMENT OF

THE REQUIREMENTS FOR THE DEGREE OF

MASTER OF APPLIED SCIENCE

in the Department

of

Electrical Engineering

We accept this thesis as conforming to the standards required from candidates for the degree of Master of Applied Science

Members of the Department

of Electrical Engineering

The University of British Columbia

April, 1958

## ABSTRACT

The large numbers of functions required in computations concerned with systems simulation have often resulted in function generators being very bulky, inflexible and expensive pieces of apparatus. This is because a separate system is often required for each function to be generated.

The method proposed here enables a large number of functions to be generated by a minimum of equipment. Moreover, the arrangement is very flexible and should prove accurate to within 1%.

This unit is designed for a time sequential analogue computer. This method of computation enables the functions F(X) to be stored and each sampled at a discrete value of X by a single sampling system. The functions are stored as photographs mounted around the surface of a rotating drum. Each function is sampled in turn by a beam of light and a photocell system. The position of the beam, (controlled by a galvanometer), determines the value of X at which the function is being sampled. The output from the photocell is arranged to indicate the value of F(X). In this unit up to 1000 samples per second can be made from 15 different functions - all at different values of X if necessary. The flexibility is such that the number of functions stored could be greatly exceeded with very little extra equipment.

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## ACKNOWLEDGEMENT

The work for this thesis is part of the Analogue Computer Project being conducted in the Department of Electrical Engineering at the University of British Columbia. The project is sponsored by the Defence Research Board, Department of National Defence, Canada, under Grant Number DRB C-9931-02(550-GC).

Many thanks are due to Dr. E.V. Bohn, under whose guidance this work was performed, and to Dr. F. Noakes, grantee of the project. Appreciation is also expressed for the willing assistance given to the author on many occasions by other members of the University Staff.

The author is indebted to the Northern Electric Company which granted him a scholarship in 1957, thus enabling him to continue his studies.

## INTRODUCTION

In systems simulation large numbers of functions are required in the computation processes. These functions have to be generated by some means. There are a variety of methods available for function generation, each having its own advantages and disadvantages. These methods had to be considered in the light of the requirements of the computer for which this generator was designed. In this case, a versatile system for generating a large number of functions (15 or more) is required. The accuracy must be to within 1 or 2%.

The usual methods of function generation are divided in to two main categories, these are: -

(a) Electronic methods.

(b) Electro-mechanical devices.

The electronic systems employ such devices as the cathode ray tube photoformer (Ref. 1, p. 248). Another electronic system approximates a waveform by a series of straight lines or curved segments using a network of resistances and diodes (Ref. 2, p. 315). Both these systems would prove very expensive in this case since the equipment would have to be duplicated for each function to be generated. Moreover it is doubtful if the accuracy could be maintained at the required level.

Among the electro-mechanical devices are non-linear potentiometers wound to represent particular functions, or linear ones operated by cams cut to represent the required functions. These function generators are servo driven and have a poor frequency response when coupled together. The large number of servos and potentiometers required make this system bulky, expensive and very inflexible.

Another type of electromechanical device available for function generation is the galvanometer. Functions can be stored as photographs on 35 mm film and mounted around the edge of a drum. This drum rotates and information can be selected from each function in turn by a system employing a beam of light, (positioned by the galvanometer mirror) and a photo-tube. This arrangement has the great advantage that equipment does not have to be duplicated for each function. The accuracy is determined mainly by the accuracy with which the photographs can be positioned on the disc and the accuracy of defining the leading and trailing edges of the function frames.

The function generator that was previously designed by Hildebrand and Fiorentino (Refs. 3 and 4) employed a similar system and scanned the amplitude of all functions in time sequence. It produced from the photo cell a voltage proportional to the function with time as its independent variable. The sampled function was stored in its own storage unit. The speed with which the functions could be scanned accurately depended on the shape of the individual functions and the band-width of the system. Since then the storage system in the computer has been changed, so that it is only necessary to obtain one discrete value of each function at a time. This eliminates the signal distortion due to the finite band-width of the circuitry and also the sampling error.

In the present design the required functions $f_1(X)$, $f_2(X)$..... $f_1(Y)$, $f_2(Y)$ ..... etc., are stored as photographs mounted around the surface a drum called the function drum (Fig. 4). This drum rotates and information can be selected from each function in turn by means of a beam of light and a photo tube.

The system is arranged so that for a given value of X, ($X_0$ say), the function values $f_1(X_0)$, $f_2(X_0)$ ..... may be picked off in turn from the photographs and then, if desired, for a particular value of Y, ($Y_0$ say), $f_1(Y_0)$, $f_2(Y_0)$ etc., may be obtained in sequence from the photographs of the functions of Y.

To illustrate how such functions arise and why photographic representation is convenient, consider a case where a function of 2 variables is involved. Such a problem occurs when determining the plate current of a triode tube.

Here $I_b$ is a function of $E_b$ and $E_c$. Such information cannot be obtained directly from the plate characteristic curves without interpolation - which is not a convenient procedure. A 3 dimensional model could be built, but to feed information from this into the computer would be a clumsy and inaccurate process. The method which it is proposed to adopt here is a purely graphical one.

Given the plate characteristics of the tube, one curve is chosen as being typical of the group - say the one for $E_c = 0$. This we shall call $F_1(E_b)$. Then by graphical methods it is possible to find the deviation from this curve of all other curves of the group expressed as a combination of a small number of single variable functions.

For instance the functions $F_2$, $G_1$, $G_2$ could be chosen so that $I_b(E_b, E_c) = F_1(E_b) + F_2(E_b)G_1(E_c) + G_2(E_c) + \ldots\ldots$ (1). The number of terms involved would depend on the magnitude of the deviation from $F_1$ and the accuracy required. Accuracies of better than 1% are usually attainable with only the three terms used above.

When $F_2$, $G_1$, $G_2$ have been determined they would be plotted, photographed and mounted together with $F_1$ on the function drum. When the computer requires $I_b$, the function generator would determine the values of $F_1$ and $F_2$ at the required value of $E_b$ and then the values of $G_1$ and $G_2$ at the required $E_c$. These function values would be multiplied and added by the computer in the manner indicated by equation (1).

## A GENERAL DESCRIPTION OF THE FUNCTION GENERATOR

### i) The Method of Representing Functions in the Computer

Reference was made in the previous section to the fact that the computer requires only discrete values of functions at a time from the generator. This is because the computer uses a system of pulse position modulation whereby computations are carried out incrementally.

Functions are stored in the computer by pulses positioned around the surface of a magnetic drum - the memory drum of the computer. The surface of the drum is divided into ten tracks and each track is divided equally into 15 parts, called channels. These channels are separated by pulses - called the clock pulses (so named because they are the primary timing pulses in the computer). A function is represented by a pulse $P_Y$ placed between the clock pulses $CP_1$ and $CP_2$ in a channel and its position is determined by the value of the function to be represented.

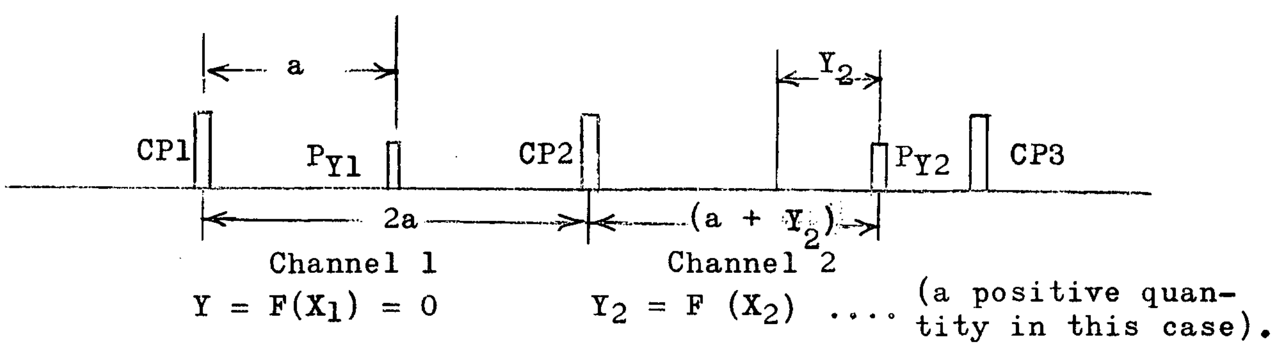



Fig. 1. Positions of Pulses in the Computer Channels

A function is allowed to have negative as well as positive values. This is achieved by considering the zero value of the function to be at a distance 'a' from the preceding clock pulse as shown in Fig. 1. The value of the function is measured from this point - positive to the right and negative to the left. For convenience, the length of channel is chosen as '2a'. The drum rotates and by means of read-write heads information can be fed into and out of the drum. The speed of the drum is fixed very accurately and is adjusted to make the length of a channel equal to 1000 microseconds.

It can now be seen that when obtaining F(X) for any value of X from the photograph of a function, the generator must present F(X) as a function pulse. This pulse must be positioned accurately with respect to the appropriate clock pulses in the computer.

ii) <u>The Operation of the Function Generator</u>

As previously stated, the photographs of functions are mounted around the surface of a drum as in Fig. 4. The function drum is rotated on the same shaft as the memory drum of the computer. This rotation causes each picture to intercept a beam of light once every revolution. A typical function photograph is shown in Fig. 2. It is completely opaque except for 2 transparent lines - the synchronizing line and the function line. As each picture passes the beam of light 2 pulses are obtained from the phototube. The first is a synchronizing pulse the leading edge of which must be lined up with its appropriate clock pulse. The second is the function pulse $P_Y$ whose position in the channel is determined by the value of F(X) at the value of X at which the photograph was being sampled.

Two conclusions follow from this process: -

a) The length of time taken for one complete picture to pass the beam of light must be that of one channel - 1000 microseconds. This is the reason why there are the same number of pictures on the function drum as there are channels on the memory drum and also why both drums must be rotated at the same speed. (Mounting them on the same shaft eliminates a synchronizing mechanism).

b) The beam of light must be positioned accurately at the required value of X before the picture begins to move across the beam.

The beam is moved by a mirror attached to the coil of a galvanometer, see Fig. 5. A current proportional to the value of X deflects the coil through the required angle and holds it there until a new X is needed. One complete channel

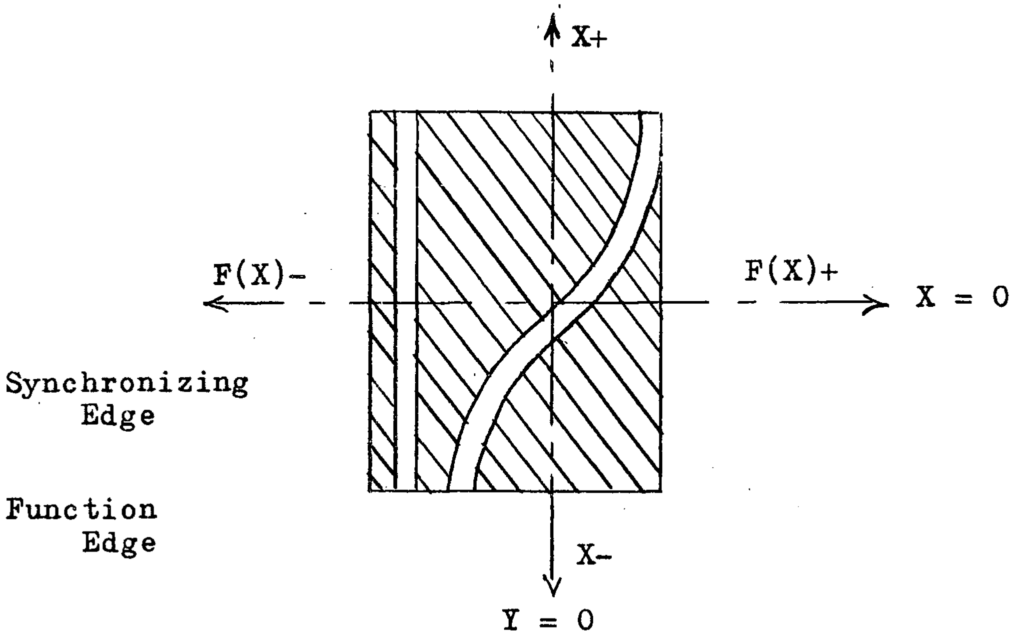



Fig. 2. A Typical Function Photograph

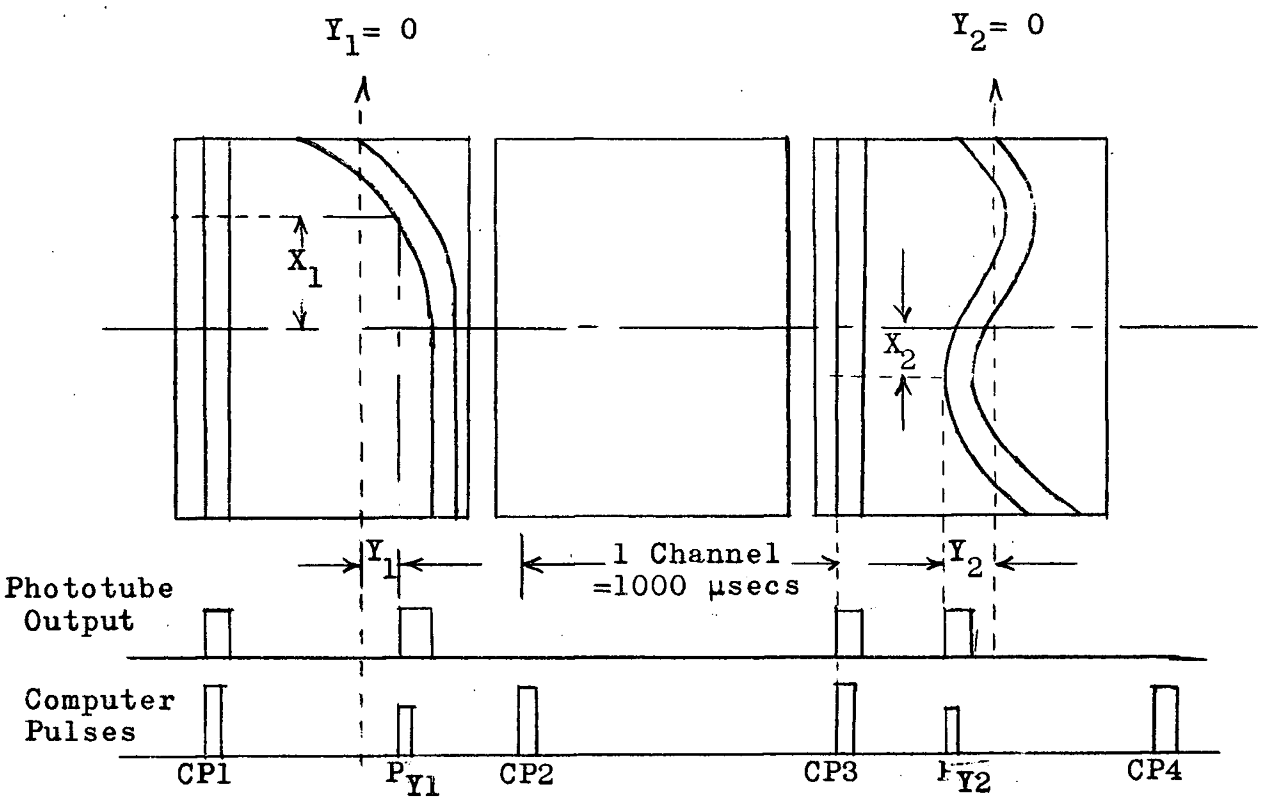



Fig. 3. Showing Generation and Synchronizing of Function Pulses $P_{Y1}$ and $P_{Y2}$

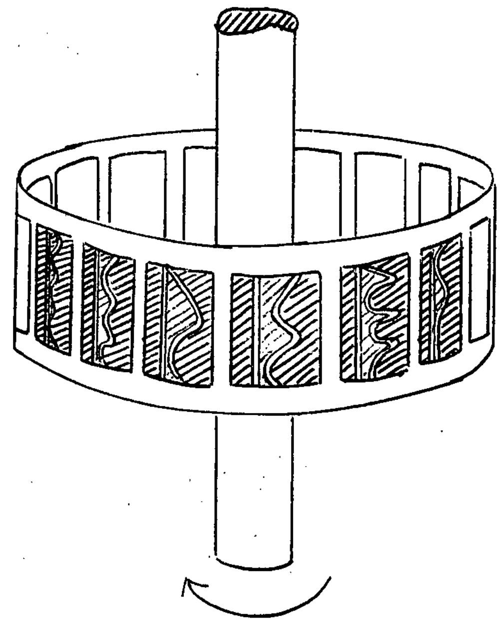


Fig. 4. Method of Mounting Functions on the Drum

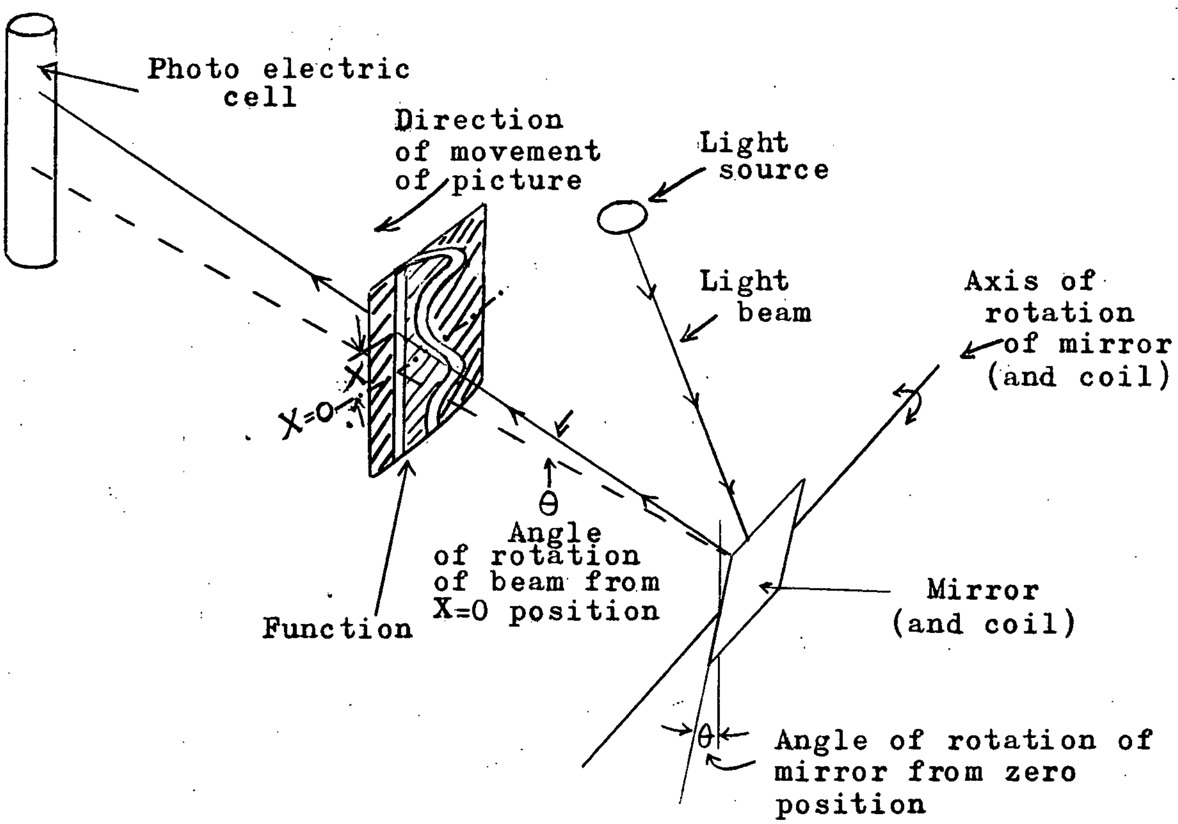



Fig. 5. Method of Sampling the Functions

- 1000 μsecs. - is normally allowed for the repositioning time of the galvanometer. However, under exceptional circumstances it might be necessary to position the galvanometer more quickly than this. Under these conditions if only a portion of each channel were used to accommodate the functions, the remaining time could be utilized for positioning the galvanometer. It is for this reason that it was decided to investigate just how quickly it is possible to position the galvanometer. It is towards this end that most of the work of the project has been devoted.

It can now be seen that the function generator must comprise three separate parts: -

a) The optical system, including the function drum.

b) The circuitry connected with the photomultiplier tube to feed function pulses into the computer.

c) The galvanometer positioning circuit, which must supply a driving signal which will position the galvanometer as quickly as possible and hold it there until a new deflection is needed.

## iii) The Theory of the Galvanometer Response

The response to a step input of a damped oscillating system, where the damping force is proportional to the velocity, is of the form: -

$$\theta(t) = \theta_{ss}(1 - e^{-\alpha t}\text{Cos}\beta t)$$

Where $\theta(t)$ is the angular deflection after time t.

$\theta_{ss}$ is the steady state deflection due to the step.

$\alpha$ is the attenuation factor of the system.

$\beta$ is the damped resonant angular velocity.

Fig. 6 shows a plot of $\theta$ against time.

In order to position such a system more rapidly at $\theta_{ss}$ than is possible with a step input alone, higher values of acceleration and deceleration are necessary. These are obtained by applying a very much larger step input than is required for the final steady state position. In order to stop and hold the system at the required deflection, a large decelerating step must be applied at the appropriate moment which just brings the velocity to zero at the required final position. A holding torque is then applied to keep the deflection at this value until a new movement is required.

The complete input is shown in Fig. 7a. It consists of 3 step inputs, each of which excites a separate transient response in the system of the form $\theta_{ss}e^{-\alpha t}\text{Cos}\,\beta t$. Smith (Ref. 5) in his work on rapid positioning servo systems has pointed out

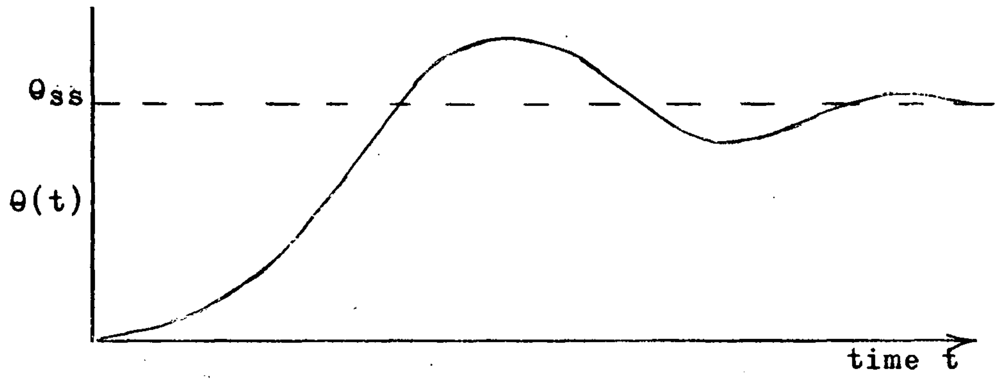



Fig. 6. The Response of a Damped System to a Unit Step Input

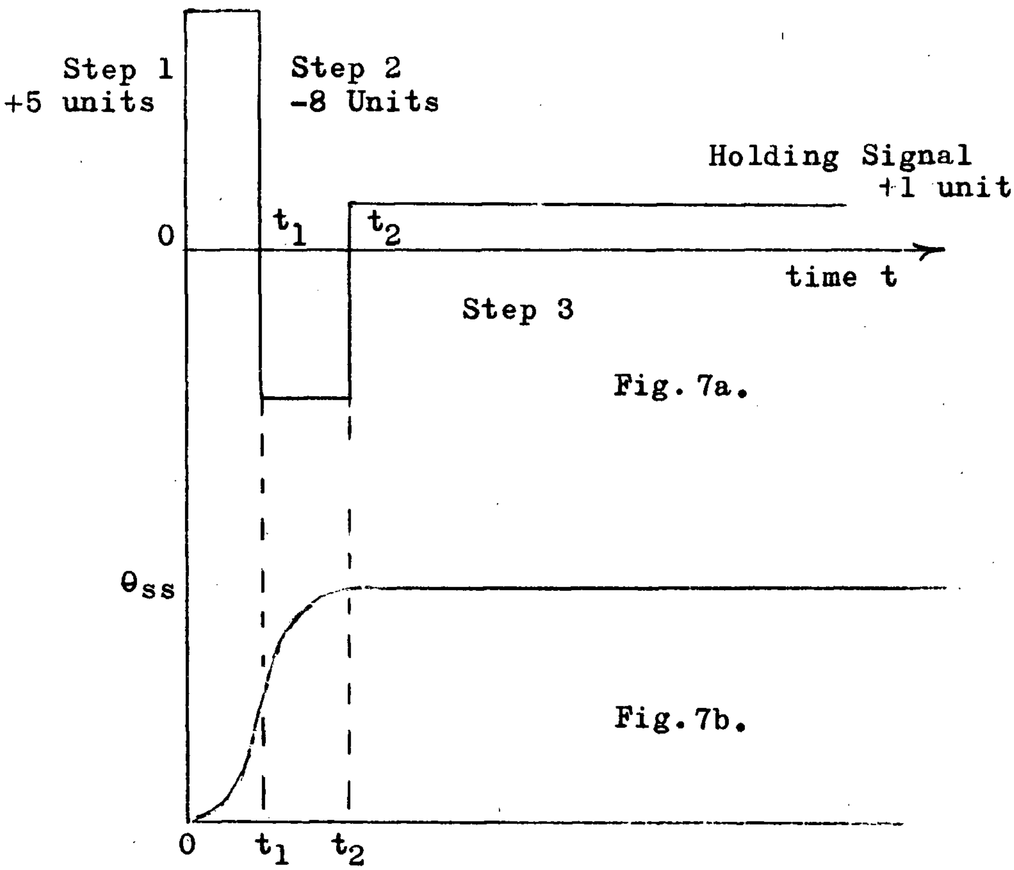



Fig. 7a. Shows a Driving Signal for K=4
b. Shows the Resulting System Response

that the responses to these 3 steps can be represented by 3 rotating shrinking vectors. The initial amplitudes of the vectors are proportional to the step inputs producing them. They are rotating with the same angular velocity and all shrinking at the same rate ( $e^{-\alpha t}$). They can thus be drawn on a diagram, separated from each other by angles proportional to their mutual time displacements.

The requirements for correct positioning are: -

(a) That the arithmetic sum of the three input steps must be the steady state deflection desired.

(b) That at the instant when the third step is applied the vector sum of the three transients must be zero.

The first condition ensures that the correct steady

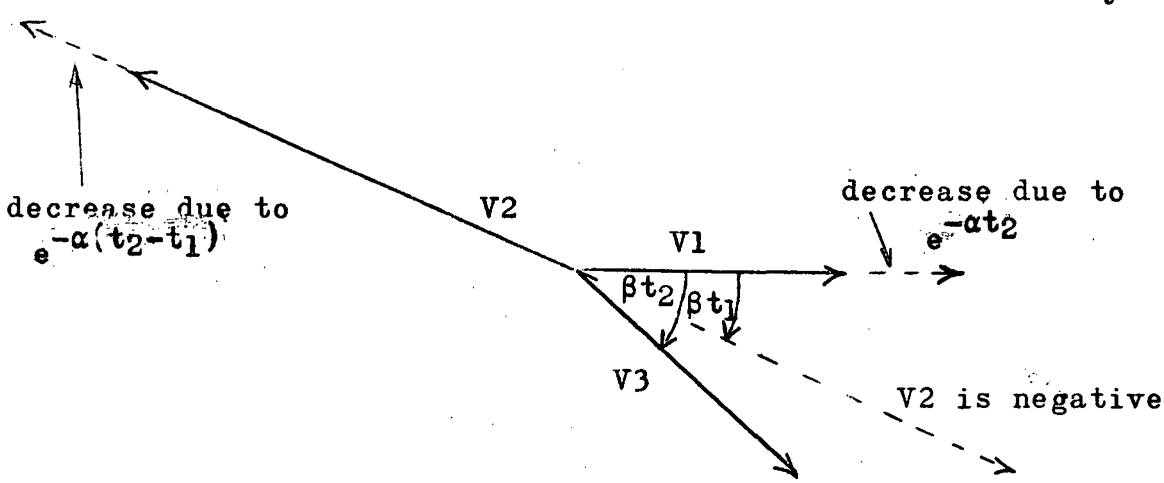



__Fig. 8.__ __The Vectors Representing the Transient Response of a Damped System to a Driving Signal__

state deflection is obtained. The second means that when step 3 is applied, the velocity of the system is zero and its position is the steady state deflection required. Fig.8 represents the vectors drawn at this instant $t_2$. Notice that the initial values of the transients represented by the vectors V1 and V2 will be larger by factors of $e^{\alpha t_2}$ and $e^{\alpha(t_2-t_1)}$ respectively.

When the above theory is applied to the galvanometer, it should be noted that the coil is immersed in fluid and thus the turbulence resulting from the high velocities involved here is likely to introduce non-linearities to the system. As a result of this it was not possible to compute a value for $\alpha$ under the pulsed conditions used here. It is thought, however, that the value it assumes is probably smaller than that for the linear case. If this assumption is correct, then the effect of the $e^{-\alpha t}$ terms may be neglected when attempting to predict an approximate value of positioning time for the galvanometer.

Values were computed for a driving signal represented by the vectors V1 = +5, V2 = -8, V3 = +4 - i.e. one with a pulse amplitude to holding voltage ratio K of 4:1 and a steady state value of unity. The damped resonant frequency of the galvanometer was taken as 325 c/s and the effects of the $e^{-\alpha t}$ terms on V1 and V2 at time $t_2$ were neglected. The results were as follows: -

The total positioning time $(t_1 + t_2)$ — 450 $\mu$secs.

The duration of the first pulse $t_1$ — 205 $\mu$secs.

The duration of the second pulse $(t_2 - t_1)$ — 245 $\mu$secs.

For a similar signal where K = 6, the theory gave: -

$(t_1 + t_2)$ — 380 $\mu$secs.

$t_1$ — 180 $\mu$secs.

$(t_2 - t_1)$ — 200 $\mu$secs.

It was decided that the circuit to drive the galvanometer should be capable of producing signals of the form considered above. The value of K was to be adjustable up to a maximum of 10:1. This, it was considered, would involve the largest pulse current that the galvanometer would accept without damage. - 160 milliamps for a beam deflection of 16 mm. at the function drum. The pulse durations were to be adjustable up to 250 $\mu$secs.

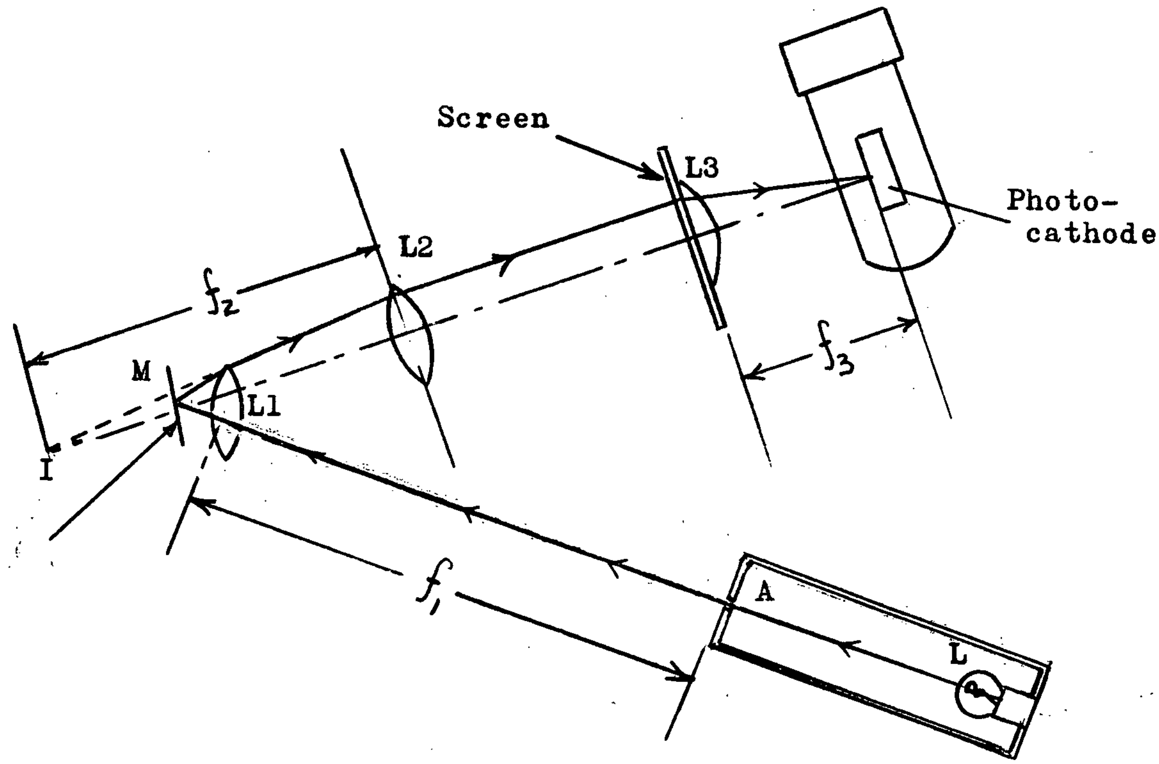
## THE OPTICAL SYSTEM

The final version of the optical system has not yet been designed, but tests have been carried out with the system described here to determine how small a beam of light can be obtained and also to examine the transient response of the galvanometer.

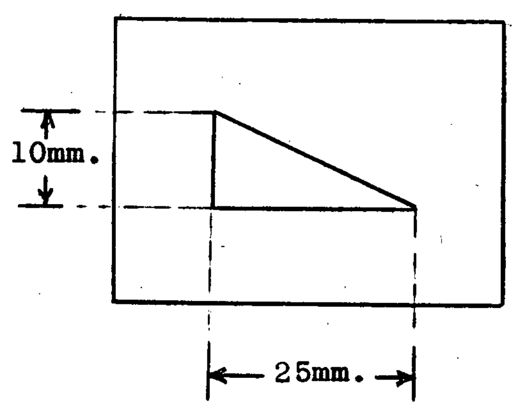
The system was originally arranged as shown in Fig. 9. A 30 watt projection bulb and the small aperture A produced a narrow light beam. This was reflected by the galvanometer mirror M, shown in a deflected position, on to the screen which represented the function drum. The beam was allowed to pass through the screen and thence onto the cathode of the phototube. The system was arranged so that for 16 milliamps through the galvanometer coil, a deflection of 16 mm. was obtained at the screen.

The image at the screen was about 0.5 mm. in diameter. A beam of small width is necessary for good resolution of the functions along the X axis of the photographs, but the dimension in the Y direction is less critical.

A parallel beam was obtained by placing the galvanometer lens L1 at its effective focal length from the aperture A. Lens L2 was positioned so that for any deflection of the galvanometer, it produced a beam parallel to the axis of the system. This was necessary in order that lens L3




<u>Fig.9</u> <u>The Optical System</u>




<u>Fig.10</u> <u>The Test Screen with Tapered Slot</u>

could reduce the movement of the light on the photocathode from the 32 mm. maximum obtained at the screen. Later in the tests, when the galvanometer response was being examined, it was found necessary to eliminate all movement of the beam on the cathode. Hence L3 was a high quality lens system placed at its focal length from the cathode. Since the incident beam to L3 is always parallel to the axis, the refracted one must pass through the focal point of the lens - i.e. on to the same point of the photocathode.

In order to test the transient response of the galvanometer the voltage output from the phototube was required to be proportional to the deflection of the galvanometer. The aperture was replaced by a rectangular slot which produced a beam 15 mm. high and 0.5 mm. wide. This beam scanned a tapered slot shown in Fig. 10. As it moved across the screen, the change in the quantity of light passing through the slot was proportional to the deflection of galvanometer. However, in order to obtain reasonable linearity from the phototube, the image on the cathode had to remain perfectly stationary for all deflections of the beam. This was achieved by the method referred to earlier. Only fair linearity between deflection and voltage output from the phototube was obtained but it proved sufficiently good to test the transient response of the galvanometer.

For future tests on the galvanometer response, the system should be modified. In order to obtain a voltage output from the photomultiplier that is proportional to the deflection of the galvanometer, without altering the normal arrangement of the optical system for function generation, it is suggested that: -

a) The tapered slot be replaced by a linearly graded photographic film. The normal beam of light could then be used and the light falling on the cathode would still be proportional to the deflection of the galvanometer.

b) The 931-A phototube be replaced by a type that has no grid wires to interrupt the light beam and also has a more uniform cathode surface.

## THE PHOTOMULTIPLIER SYSTEM

The requirements for this part of the generator are that the pulses produced from the photomultiplier must themselves generate pulses which are accurately positioned with respect to the clock pulses in the computer. The problem here is to ascertain that the resulting pulses are always initiated by the same quantity of light falling on the photocathode.

The method by which it is proposed to accomplish this is as follows. Each output pulse from the phototube is fed to a tuned amplifier stage. The step input causes the plate tuned circuit to produce a series of damped oscillations. The time at which this output voltage first returns to zero depends on the natural frequency of the tuned circuit and the shape of the leading edge of the phototube pulse. It does not depend on the amplitude of this pulse. Hence this point in the waveform always occurs at the same time after the beginning of the phototube output and it is this zero cross-over point which will be detected by a switching circuit. (Rapid restoration of the tuned circuit is desirable. This can be achieved by means of a damping diode). The crossover point can be detected to within 0.1 volts by a circuit using low voltage switching transistors. This switch will then operate a circuit to produce the synchronizing and function pulses from the function generator.

The pulses produced by this circuit are accurately positioned with respect to the synchronizing and function edges on the photographs. When the synchronizing pulses are aligned with the clock pulses, the function pulses will then be accurately positioned in their respective channels.

The main limitations to the accuracy of this system are: -

a) The accuracy with which the synchronizing and function edges of the functions can be determined.

b) The accuracy with which the centres, (the X = 0 axies), of all the functions can be aligned on the drum.

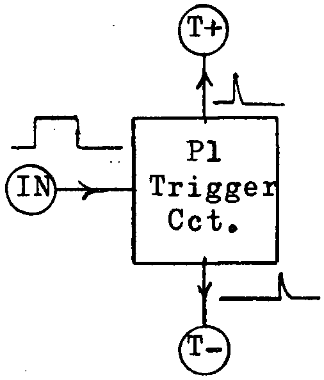
c) The resolution of the light beam in the X direction. Provided that the functions have no discontinuities, the error from this cause is expected to be very small - less than 1% - with a beam 0.5 mm. wide.

# THE GALVANOMETER POSITIONING CIRCUIT

## i) The Functions of the Block Diagram Components

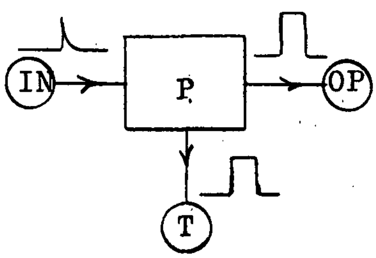
The Block Diagram of the galvanometer positioning circuit is shown in Fig.11. The functions of the components of this diagram are described below.

### The P1 Trigger Circuit




A positive going pulse applied to the input terminal produces a positive trigger pulse at the output terminal marked 'T+', while a negative going edge at the input produces a positive trigger pulse at the 'T-' output terminal.

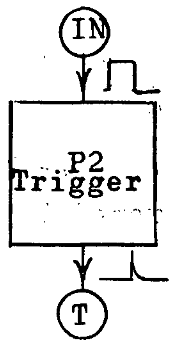
### The Phantastrons




There are four of these in the complete circuit P1+, P2+, P1- and P2-. A positive going trigger pulse at the IN terminal will produce a +140 volts pulse at the output. The duration of this pulse can be adjusted between the limits 0 to 250 $\mu$secs.

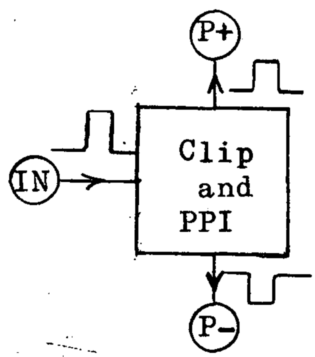
In the P1 phantastrons an extra output terminal 'T' is provided. The two output signals are identical but one is isolated from the other.

## The P2 Trigger Circuit



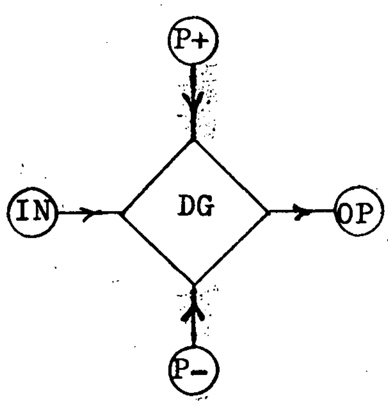

This circuit produces a positive trigger pulse from the trailing edge of the P1 pulses which are fed into it.

## The Clip and PPI Circuit




The function of this circuit is to produce pulses which operate the diode gate with which it is associated. The +140 volt phantastron pulses are applied at the input terminal and the circuit produces 2 opposite going pulses of 90 volts amplitude and of the same duration at the output terminals P+, P-.

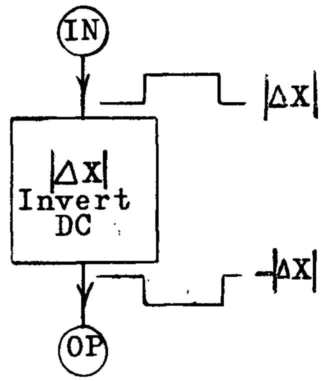
## The Diode Gates DGA and DGB




These gates have identical circuits. Each is operated by the output pulses from its own PPI circuit. The voltage to be gated is applied to the IN terminal. The output is a pulse whose amplitude is equal to the input voltage and whose duration is that of the gating pulses.

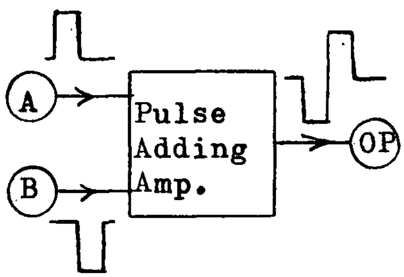
The $|\Delta X|$ Inverter

This is a DC operational amplifier whose gain is precisely -1.



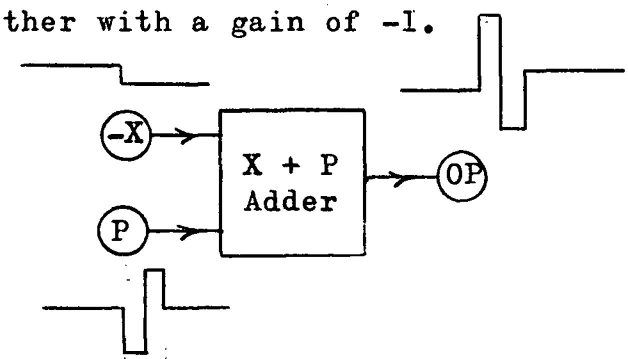

The Pulse Adding Amplifier

Also a DC operational amplifier, which combines both its input signals and amplifies them with a gain of -4.




The X and P Adder

Another DC operational amplifier which adds its two input signals together with a gain of -1.




The Galvanometer Drive Circuit and the AC Drive Inverter

These circuits are driven by the X + P Adder and are contained within its feedback loop. They are arranged to produce

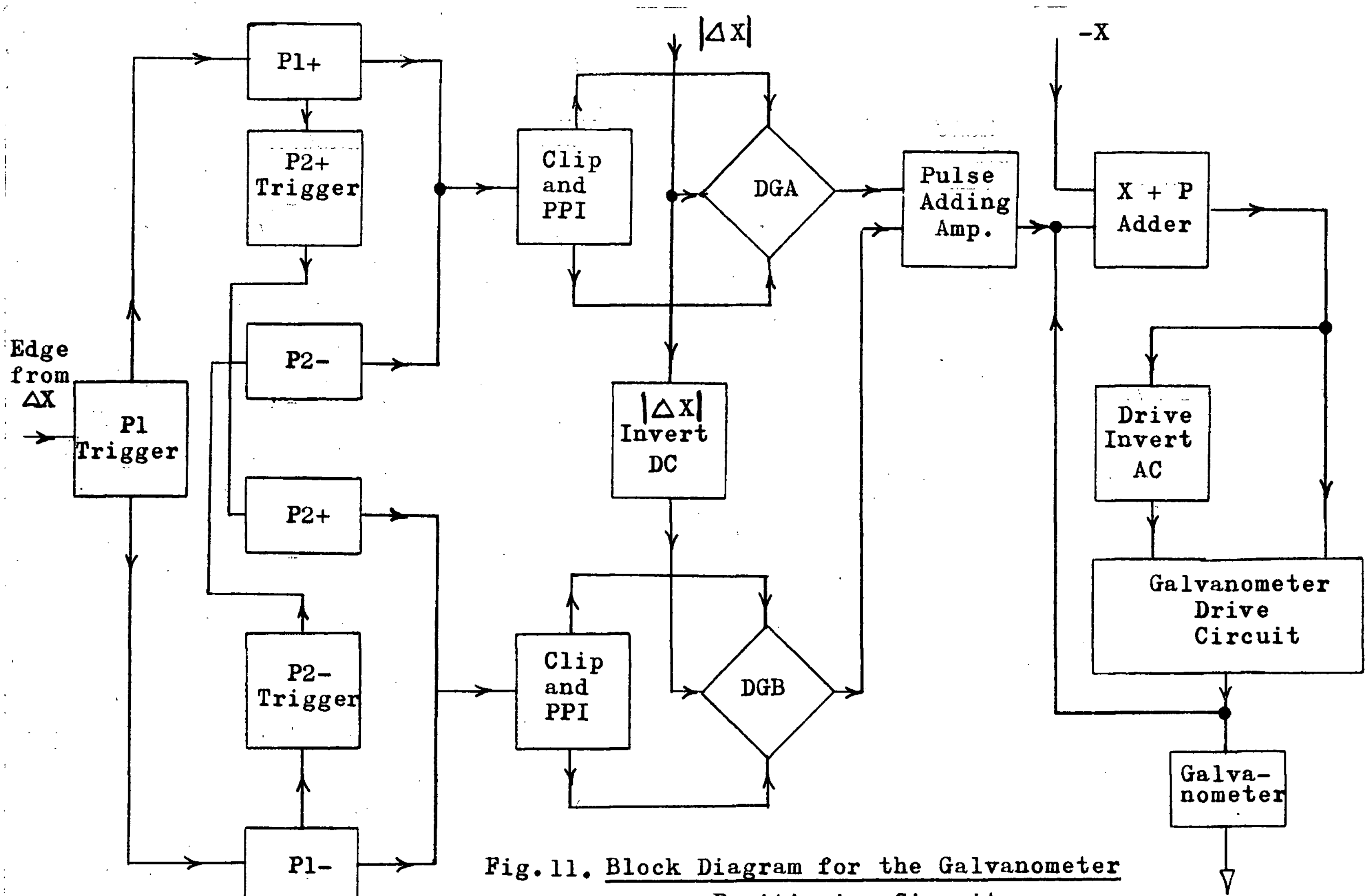



Fig. 11. Block Diagram for the Galvanometer Positioning Circuit.

the pulsed and holding currents required to deflect the galvanometer. Their arrangement is as depicted in the block diagram.

ii) <u>The Operation of the Galvanometer Position Circuit</u>

The operation of this circuit is described with reference to the Block Diagram Fig. 11 and the Waveform Coincidence Diagram Fig. 12. It will be seen from the Block Diagram that a step voltage of the same sign as $\Delta X$ is fed to the Pl Trigger Circuit. If $\Delta X$ is positive then phantastron Pl+ is triggered. The output pulse from Pl, Fig. 12B, is fed into the clipping circuit and thence to the Paraphase Inverter which produces the pulses to operate Gate DGA. Voltage $+|\Delta X|$ is applied to the input of DGA and this gate produces a pulse of the same duration as the original Pl pulse, but its amplitude is equal to $+|\Delta X|$ (see Fig.12D). The output from DGA is fed to one input terminal of the Pulse Adding Amplifier. Meanwhile, the trailing edge of the pulse from Pl+ triggers the P2+ phantastron via the P2+ Trigger Circuit. The resulting P2+ pulse, (Fig. 12C), is also clipped and fed to its paraphase inverter. The output from the inverter is made to operate gate DGB. The input to this gate is a voltage $-|\Delta X|$ and hence the output is a pulse whose duration is that of the P2+ pulse and whose amplitude is $-|\Delta X|$, (Fig. 12E). This pulse follows immediately after the one from DGA and is applied to the other terminal of the Pulse Adding Amplifier.

The Pulse Adding Amplifier combines its two input pulses and amplifies them by a factor of four, (Fig. 12F). This waveform is then fed to the Galvanometer Drive Circuit which provides the

Waveforms are drawn for maximum deflection of galvanometer from 0 to X and back again from X to 0. For these conditions $X = |\Delta X| = 15$ volts.

A. Holding Signal X

B. Input Pulses to DGA PPI

C. Input Pulses to DGB PPI

D. Output Pulses from DGA Amplitude = $+|\Delta X|$

E. Output Pulses from DGB Amplitude = $-|\Delta X|$

F. Output from Pulse Adding Amplifier Amplitude = $\pm 4|\Delta X|$

G. Complete Waveform from X + P Adder which is fed to the Galvanometer

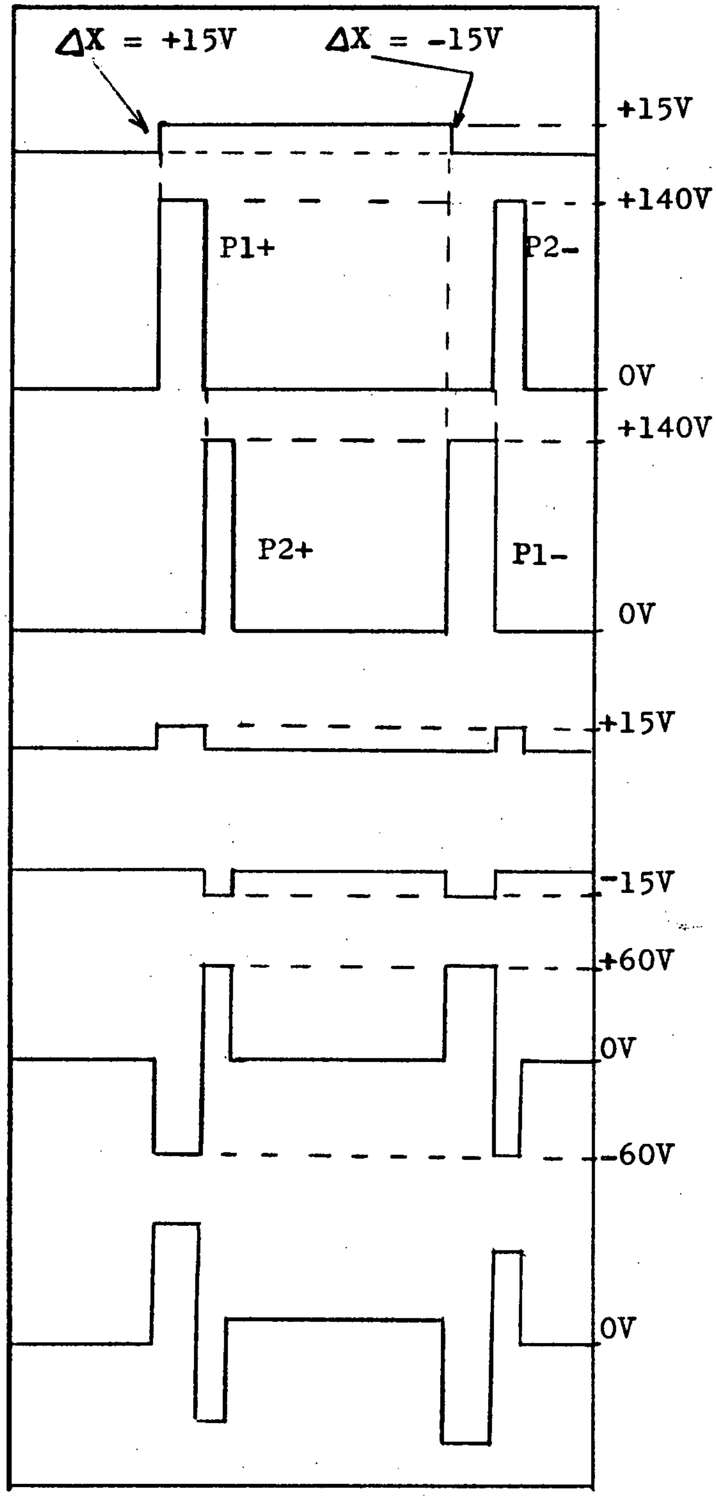



Fig. 12. Waveform Coincidence in Galvanometer Positioning Circuit

current to move the galvanometer to its new position and to hold it there.

However, we have only dealt with the case when $\Delta X$ is positive. When $\Delta X$ is negative, a negative edge triggers phantastron P1- via the P1 Trigger Circuit. (See Fig.12C). It operates gate DGB via its paraphase inverter circuit. The output of DGB is a P1 pulse of amplitude $-|\Delta X|$, (Fig.12E). The trailing edge of the P1- pulse triggers phantastron P2- which operates gate DGA. DGA produces a P2 pulse of amplitude of $+|\Delta X|$, (Fig.12D). These pulses from the two gates are combined and amplified in the Pulse Adding Amplifier. They are then added to the holding voltage -X as before and applied to the Galvanometer Drive Circuit.

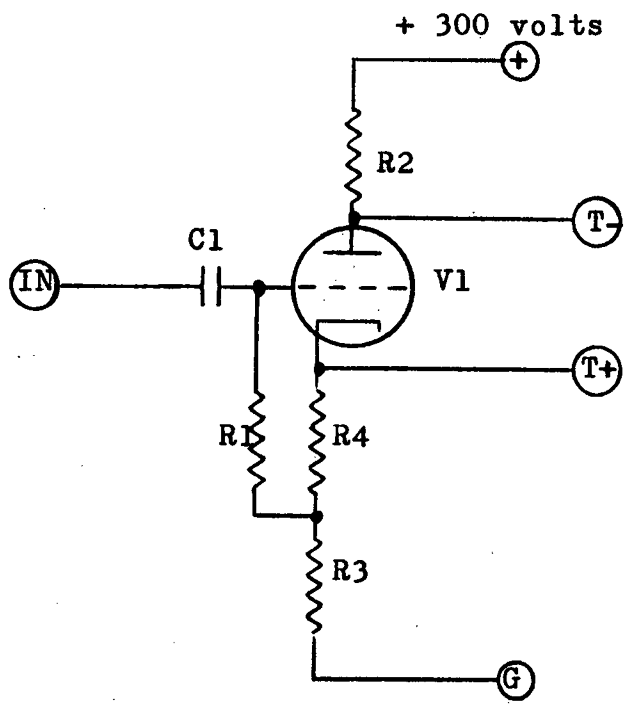
The complete sequence of operations necessary to move the galvanometer from one position to another and back again has now been described.

iii) <u>Circuit Details</u>

<u>The P1 Trigger Circuit (Fig.13).</u>

This circuit is at present designed to operate in conjunction with the test circuit. It requires a step voltage input of 60 volts amplitude to trigger the phantastrons. This step voltage must be applied whenever a new deflection of the galvanometer is required and must have the same sign as $\Delta X$. i.e. if $(X_2 - X_1)$ is positive then the step voltage must be positive and vice versa.

The trigger circuit comprises a differentiating input circuit R1, C1 (of time constant 1 microsecond), followed by a paraphase inverter - tube V1. When the step input to C1 is positive, i.e. when $\Delta X$ is positive, a positive pulse occurs at the cathode of V1, this is fed to the input of phantastron P1+. When $\Delta X$ is negative a positive going pulse is fed to P1- from the plate of V1. Negative pulses from the trigger circuits do not affect the phantastrons.




C1 - 100 pf

R1 - 10K 1 watt

R2-3- 33K

R4 - 470 ohms

V1 - 12AT7

Fig. 13. The P1 Trigger Circuit

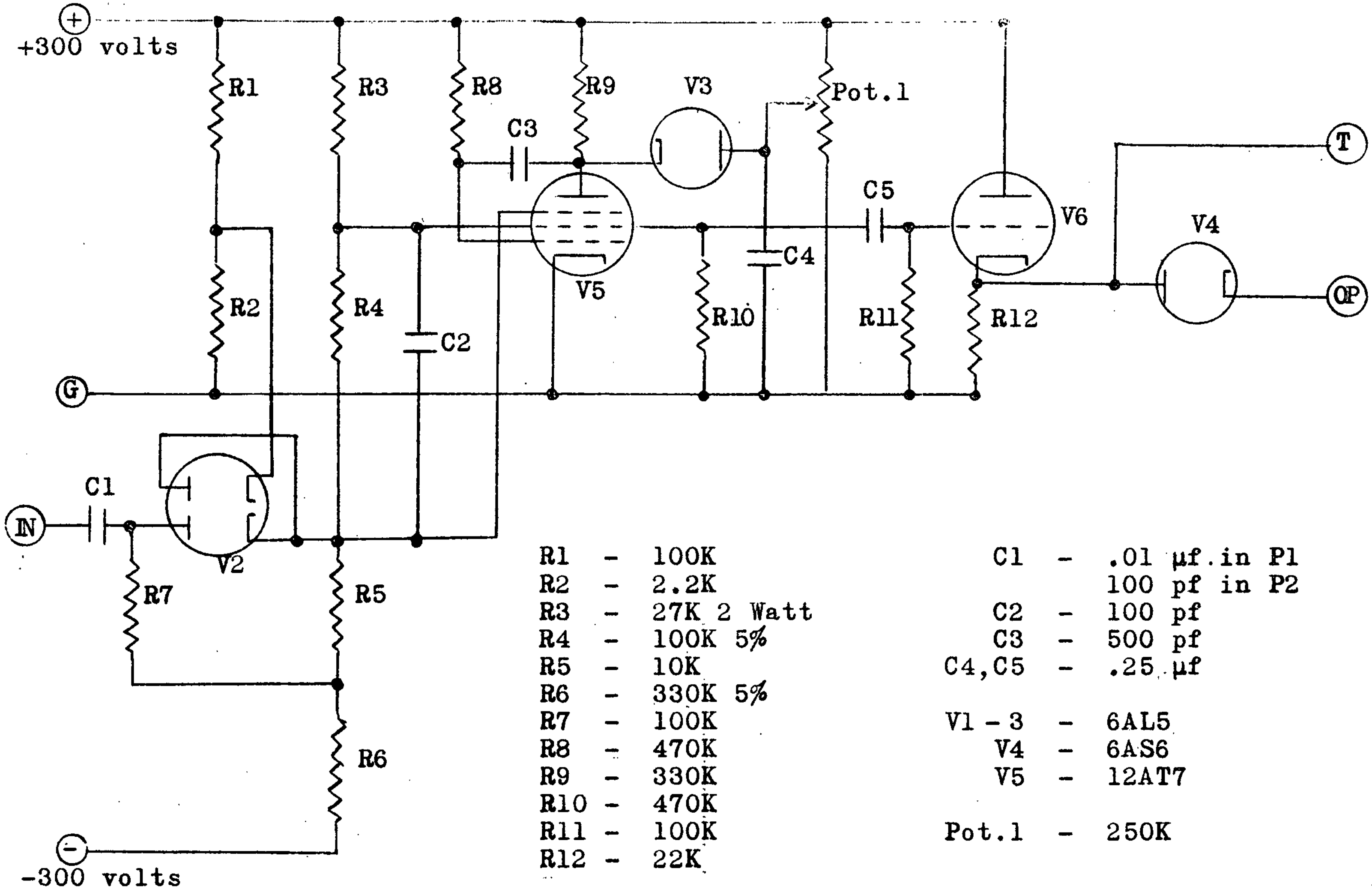
Since C1 is only 100pf., parasitic capacitance at the grid of V1 reduces the amplitude of the differentiated signal and an input of 60 volts is required to produce the 50 volt trigger pulses from the cathode and plate of V1 which are necessary to trigger the phantastrons.

Since positive pulses are required at both plate and cathode, V1 must be normally conducting. About 4.5 mAs from the 300 volts supply maintains 150 volts at the plate and 70 volts at the cathode, with a bias of 2 volts supplied by R4.

The Phantastron Circuit (Fig.14)

The four phantastron circuits are substantially identical. A trigger pulse from the appropriate trigger circuit operates the tube V5 which produces a positive pulse of about 140 volts amplitude from its screen grid. This pulse is passed to a cathode follower V6 and thence via a blocking diode V4 to the gating circuits. In the case of the P1 phantastrons the trailing edge of the output pulse has to trigger the P2 phantastrons. Hence an extra output is provided from the cathode of V6. This goes to the P2 trigger circuits.

The operation of the circuit in detail is as follows. The phantastron tube V5 (6AS6) has its suppressor held at about -30 volts by the resistor chain R3 - R6 connected between the +300 volts and the -300 volts supplies. The grid resistor R8 (470K) is taken to the +300 volts supply. Hence the plate is cut off by the suppressor voltage while the screen is conducting and held at about +50 volts. A positive trigger pulse of 35 volts at the suppressor, via C1 and diode V2, causes the plate to conduct. (Note that this means a 50 volt pulse at the input




| | | | | | |
|---|---|---|---|---|---|
| R1 | - | 100K | C1 | - | .01 µf.in P1 |
| R2 | - | 2.2K | | | 100 pf in P2 |
| R3 | - | 27K 2 Watt | C2 | - | 100 pf |
| R4 | - | 100K 5% | C3 | - | 500 pf |
| R5 | - | 10K | C4,C5 | - | .25 µf |
| R6 | - | 330K 5% | | | |
| R7 | - | 100K | V1 - 3 | - | 6AL5 |
| R8 | - | 470K | V4 | - | 6AS6 |
| R9 | - | 330K | V5 | - | 12AT7 |
| R10 | - | 470K | | | |
| R11 | - | 100K | Pot.1 | - | 250K |
| R12 | - | 22K | | | |

Fig. 14. The Phantastron Unit Circuit Diagram

terminal due to drop through diode and stray capacitance). After a small initial fall of about 5 volts, the plate voltage then runs down linearly at a rate of 1.2 volts per microsecond (see footnote to this section). This fall ends when the plate voltage is caught by diode V3, the plate of which is kept at a positive voltage determined by Pot. 1. When this happens the plate returns towards $E_{bb}$ exponentially at a rate determined by the time constant formed by R9, C3 (165 μ sec). The plate voltage of V3 can be varied from 0 to 300 volts and thus the duration of the V5 plate run down is determined by adjustment of Pot. 1.

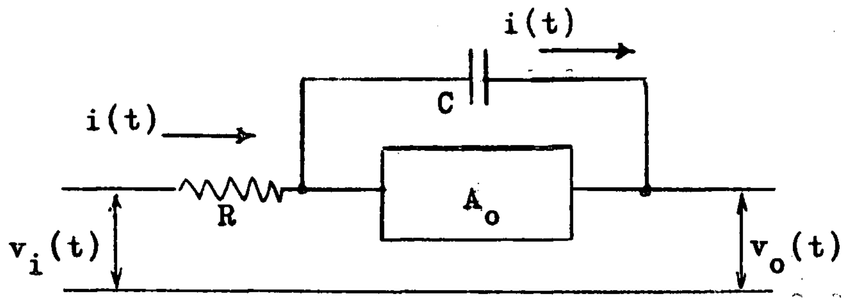
When V5 plate conducts, the tube current is switched from the screen which thus rises about 140 volts and remains there until the plate rundown ends. When this occurs the plate current is switched off, since the suppressor has returned to -30 volts and the screen again takes over the plate current. The screen voltage of course drops back to +50 volts. Hence the short positive trigger pulse on the suppressor produces a pulse of 140 volts amplitude from the screen of V5, the duration of which is determined by the adjustment of Pot. 1. For instance, since the rundown speed of the plate is 1.2 volts per microsecond, to produce a pulse of 200 microsecond, the plate must run down through 1.2 x 200 = 240 volts. Hence the voltage setting of the Pot. 1 tap must be 300 - 240 -5* = 55 volts.

(*5 volts is the initial fall in plate volts when it starts conducting).

Referring to the other details of the phantastron circuit, the resistors R1 and R2 together with one half of tube V2 provide a clamp circuit to stop the suppressor being driven too far positive by the trigger pulse. R5 provides a bias for the trigger diode.

Footnote -

The rate of 1.2 volts per microsecond for the plate run-down is determined from the Miller circuit as below: -




For $A_o$ large $\quad i(t) = \frac{v_i(t)}{R}$

Since the input grid is kept approximately at zero volts

$$v_o(t) = \frac{1}{C}\int i.dt$$

$$\therefore \frac{dv_o}{dt} = \frac{i}{C} = \frac{v_i(t)}{RC}$$

i.e. the rate of change of the plate voltage is $\frac{v_i(t)}{RC}$

In the case of the phantastron $v_i(t)$ is constant at $E_{bb}$+ 5 volts. For this case this is 305 volts,

R is the 470K grid resistor R8

and C is the 500 pf grid-plate capacitor C3.

Hence the rate of change of plate volts is constant at : -

$$\frac{E_{bb} + 5}{R8.C3} \quad \text{volts per second.}$$

When the above values are inserted this gives 1.2 volts per microsecond.

The P2 Trigger Circuit (Fig.15)

In the case of the P1 phantastrons the P1 pulse is taken from the cathode of V6 to the P2 trigger circuit. This circuit is essentially a pulse inversion circuit comprising tube V7 - a 12AT7 triode. The 140 volts P1 pulse is fed on to the grid via limiting resistance R2 and coupling condenser C1. The output from the plate is a 200 volt negative pulse,

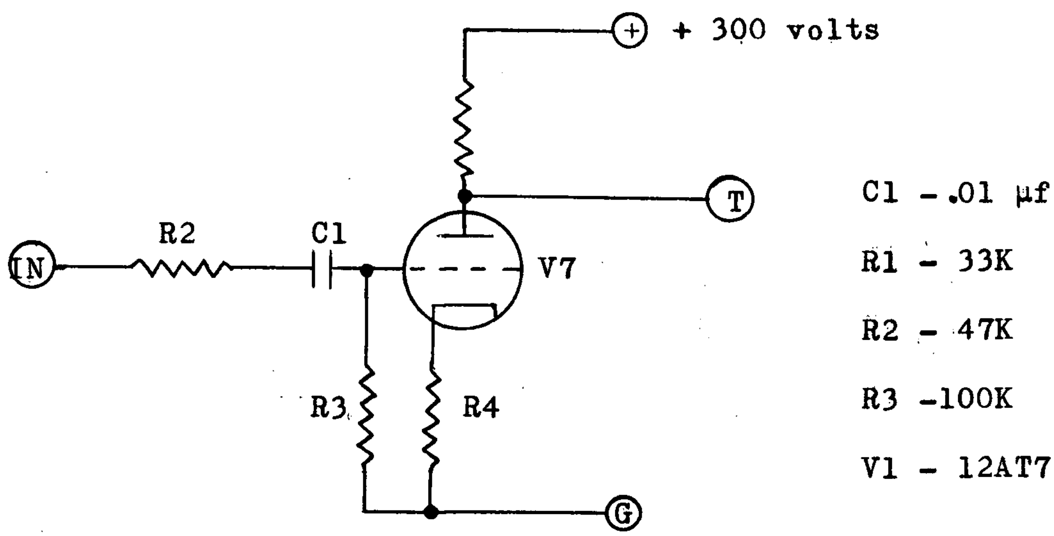


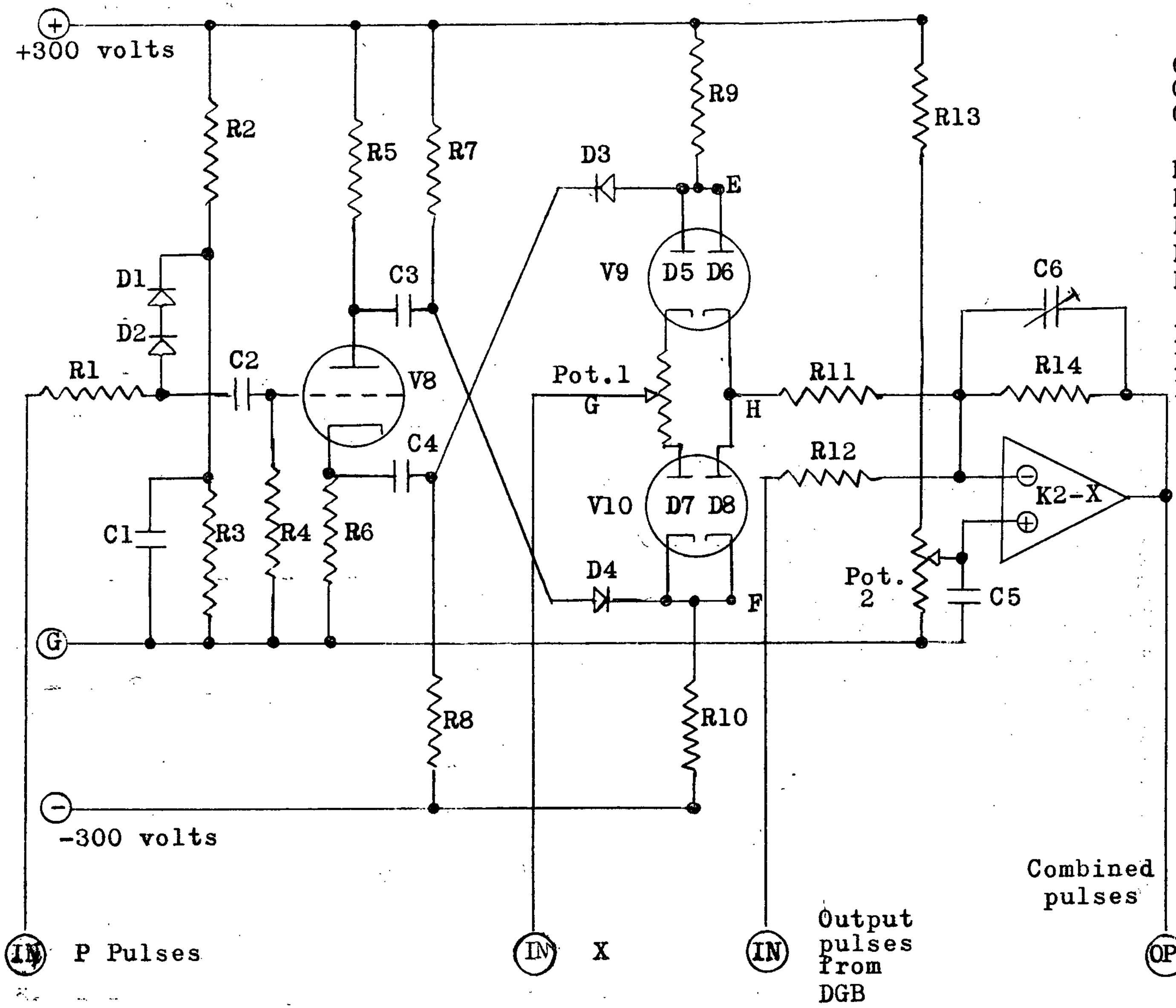

Fig. 15. The P2 Trigger Circuit

the trailing edge of which is required to trigger P2 phantastron. It will be noted from the phantastron circuit (Fig. 14) that the input condenser in the P2 phantastrons is 100 pf. This differentiates the output from V7 and provides the necessary positive trigger pulse to operate the P2 phantastron. Since the drive to V7 is +140 volts, grid current is limited by resistor R4. This ensures that the cathode follower driving it is not overloaded.

Details of the Gating Circuits (Fig.16)

With reference to the Block Diagram it will be seen that the outputs of the 4 phantastrons are combined in the following manner. P1+ and P2- together operate gate DGA, while P1- and P2+ together operate gate DGB.

The appropriate phantastron pulses are fed to the input of the circuit (Fig.16). They are clipped to an amplitude of 100 volts by the germanium diodes D1 and D2, the cathodes of which are held at 100 volts by resistors R2 (390K) and R3 (220K) across the 300 volts supply. (Two diodes in series are used since the maximum back voltage which this type of diode will stand is 80 volts). Condenser C1 (0.25μf) keeps the voltage at the junction of R2 and R3 constant during the clipping process, which does not last more than 250 microseconds - the maximum length of a phantastron pulse. After the pulses have been clipped they are applied to the grid of V8 - a 12AT7




| | | |
|---|---|---|
| C1-4 | - | 0.25 μf |
| C5 | - | 0.01 μf |
| C6 | - | 7-50 pf |
| R1 | - | 10K |
| R2 | - | 390K |
| R3 | - | 220K |
| R4 | - | 100K |
| R5-6 | - | 22K matched 1% |
| R7-8 | - | 100K 1% |
| R9-10 | - | 270K 1% |
| R11-12 | - | 82K matched 1% |
| R13 | - | 1 Meg |
| R14 | - | 330K 1% |
| Pot.1 | - | 1K |
| Pot.2 | - | 10K |
| V7 | - | 12AT7 |
| V8-9 | - | 6AL5 |
| D1-4 | - | Germanium diode type 1N-191 |

Fig. 16. Clipping Circuit, Paraphase Inverter, Diode Gate and Pulse Amplifier

triode tube. This is a paraphase inverter circuit whose matched plate and cathode resistors R5 and R6 are 22K. The outputs from the plate and cathode are 90 volt pulses - negative going from the plate and positive from the cathode. These pulses operate the diode gate via condensers C3 and C4.

The Diode Gate Circuit (Fig.16)

It consists essentially of the six diodes D2-D8 connected as shown in the diagram. For no signal conditions, the germanuim diodes D3 and D4 are conducting. The 2 pairs of resistors R9, R8 and R10, R7 are thus carrying current and hold points E and F at +45 volts and -45 volts respectively. This means that the tube diodes D5-D8 (i.e. V9 and V10) are all blocked. The output terminal, point H, is thus at zero volts.

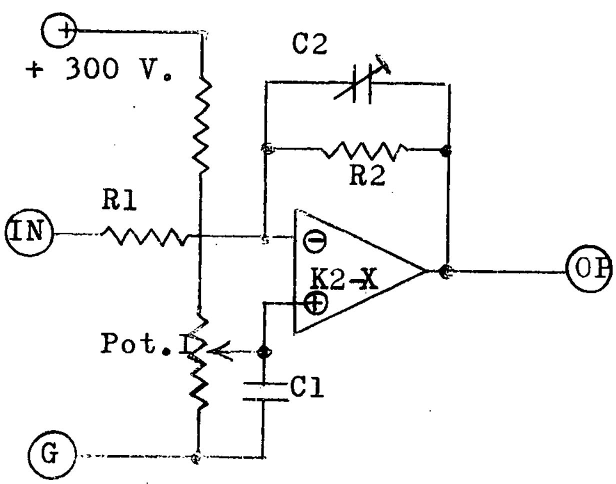
When the -90 volts pulse appears at the plate of V8 it blocks diode D4 via condenser C3. Simultaneously the +90 volt pulse appearing at the cathode of V8 blocks diode D3. The four diodes D5-D8 are now free to conduct. Since R9 and R10 are equal, the output terminal of the gate, point H, remains at zero provided that the voltage at G, the input terminal, is also zero. In fact, when the diodes are conducting, the output voltage will be equal to the input voltage to a very high degree of accuracy. This follows for positive or negative voltages and is due to the bridge configuration of the 4 diodes D5-D8.

When the gating pulses from V8 end, the gate then closes and the output voltage at H returns to zero at a rate determined by the parasitic capacitances of the diodes and the amplifier input resistor R11.

Since the voltage $+|\Delta X|$ is fed into gate DGA, the output at point H will be a pulse of amplitude equal to $+|\Delta X|$ and of duration equal to that of the phantastron pulse which operated the gate via V8. When $\Delta X$ is zero the output pulse from the gate must also be zero. Thus it is necessary to ensure that the bridge circuit formed by the diodes D5-D8 is balanced when in the conducting condition. The 1000 ohm potentiometer Pot. 1 is provided for this purpose. Adjustment of this resistor for zero amplitude pulse out when the input is zero ensures that this condition is met.

The $|\Delta X|$ Inverter Circuit (Fig. 17)

This circuit is a Philbrick K2 - X Operational




| | | |
|---|---|---|
| C1 | - | 0.01μf. |
| C2 | - | 7-50 pf. trimmer |
| R1-2 | - | 100K matched to 1% |
| R3 | - | 1 Meg. |
| Pot. 1 | - | 10K potentiometer |

Fig. 17. The $|\Delta X|$ Inverter

Amplifier connected as shown. Resistors R1 and R2 are 100K matched to within 1%. These fix the gain at unity. The input signal $|\Delta X|$ will thus provide an output of $-|\Delta X|$ . This voltage is the input for gate DGB.

R3 and Pot. 1 provide the bias for the amplifier, while condenser C1 decouples this bias supply. The trimmer C2 is adjusted to eliminate any tendency for the output signal to overshoot.

<u>The Pulse Combining Amplifier.</u>

It can be seen from the circuit diagram Fig.16, that the outputs from the two diode gates DGA and DGB are fed to the two 82K matched resistors R11, R12. These form the input terminals of the K2-X DC operational amplifier. Since the feedback resistor R14 is 330K the gain is fixed at -4.

Bias is supplied by R13 and Pot. 2. The trimmer C6 eliminates any tendency to overshoot in the output waveforms.

This amplifier has to deal with input pulses from 0 to +15 volts amplitude. It thus produces output pulses up to $\pm$60 volts amplitude which drive the X and P Adder. The pulse rise time is limited by the amplifier to about 8 microseconds.

<u>The X and P Adder and the Galvanometer Driving Circuit</u>

The description of the operation of the final stages of the circuit is initially made with reference to the simplified circuit diagram Fig.18. In this circuit there are two tubes VA and VB connected in series together with the V8 cathode resistor R15, between the +300 and -300 volts supplies. The quiescent current for these tubes is 25 mAs. It is controlled by the cathode follower action of R15, the grid of VB being held at -300 volts by R13. The grid of VA is held at a sufficiently negative voltage to keep its cathode, point A, at 0 volts. This is achieved by the feedback action of the DC amplifier, the output of which drives the grid of VA. R3 is the feedback resistor which is responsible for this control. The galvanometer G is connected between ground and point A via an adjustable resistor RG.

For positive drive from the DC amplifier, point A rises and current is fed through the galvanometer to ground. For

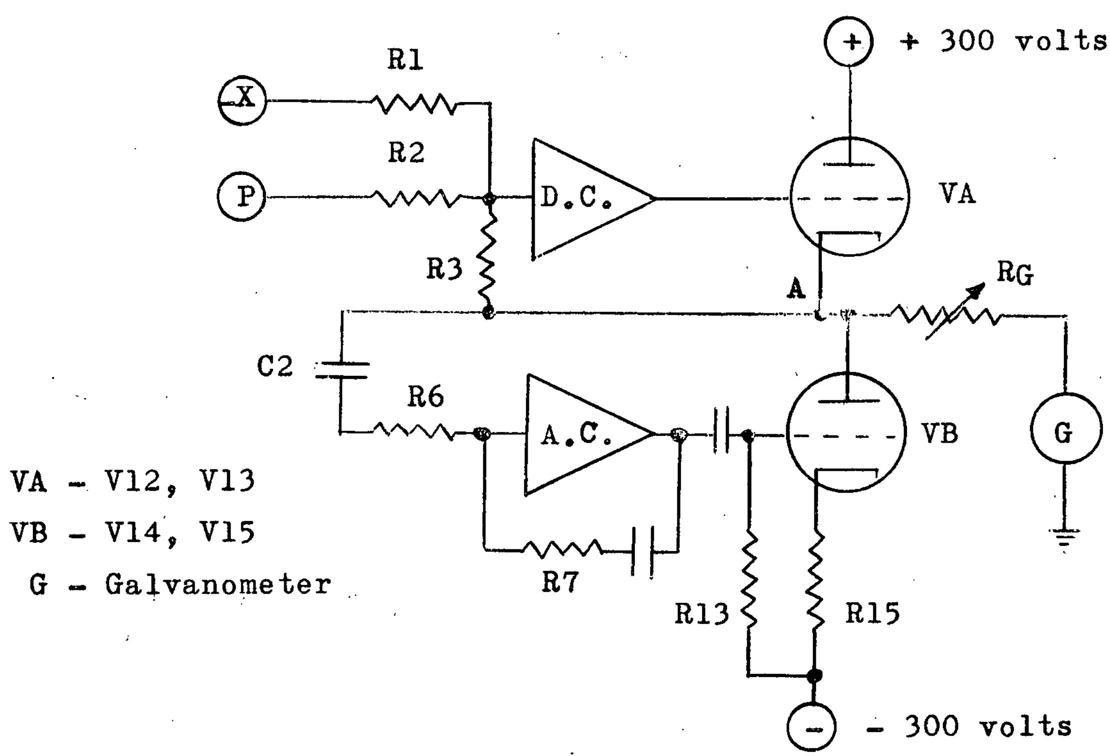
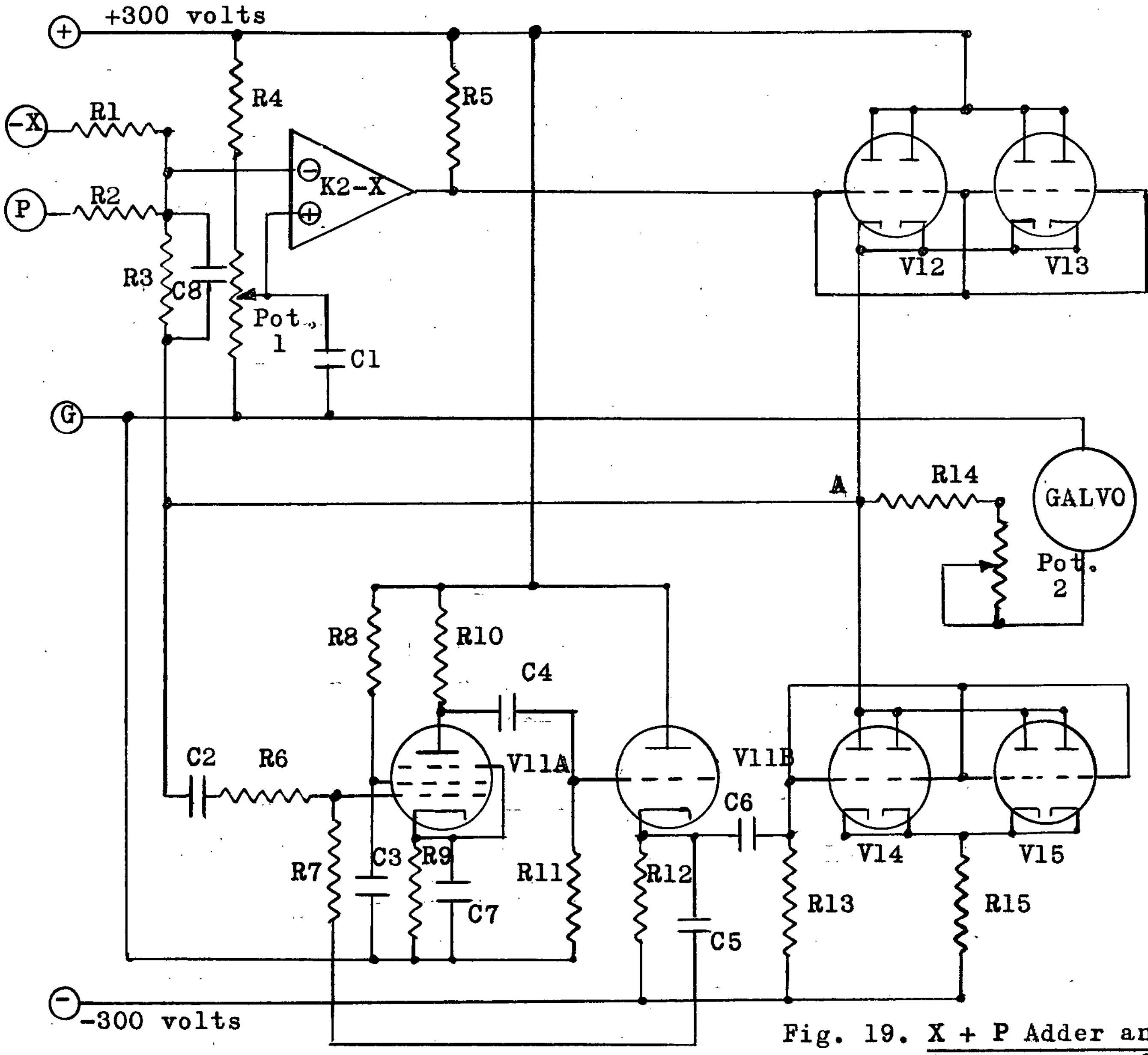



Fig. 18. The Galvanometer Drive Circuit - Simplified

small negative signals not sufficient to cut off the quiescent current in the tubes completely, the point A falls below ground and the galvanometer current is reversed. Notice that about 20 mAs or 80% of the quiescent current can be switched linearly in this manner. This will take care of the holding signals, since only 16 mAs is required for full deflection of the galvanometer. Notice also that this is supplied by a DC driving circuit so that the galvanometer can be held at any deflection indefinitely in this manner.

The current required by the larger amplitude positive going pulses can be supplied to the galvanometer in the same way. However, larger currents required by the negative going pulses cannot be supplied by this cathode follower action without more quiescent current through the tubes. This is undesirable and is the reason why the tube VB and the AC amplifier driving it are included in the circuit. They operate as follows: -

When point A is driven negative by the DC amplifier, the grid of VB is driven positive by the AC amplifier (whose input grid is connected to A via C2 & R6). This reduces the effective plate resistance of VB, more current flows from the supply and the voltage at point A is allowed to follow the fall in potential on the grid of VA. This fall is controlled by the feedback of the DC amplifier. Since the large pulsed




| | | |
|---|---|---|
| C1 | - | .01μf |
| C2-6 | - | .1 μf |
| C7 | - | 25 μf<br>25 V.D.C. |
| C8 | - | 7-50 pf. |
| R1-3 | - | 33K 1% |
| R4 | - | 1 Meg |
| R5 | - | 100K 2W |
| R6-8 | - | 100K |
| R9 | - | 270 ohms |
| R10 | - | 22K 1W |
| R11 | - | 330K |
| R12 | - | 47K 2W |
| R13 | - | 330K |
| R14-15 | - | 470 ohms<br>1 W |
| Pot. 1 | - | 10K |
| Pot. 2 | - | 1K |
| V11A-B | - | 6AN8 |
| V12-15 | - | 12AU7 |

Fig. 19. X + P Adder and Galvanometer Drive Circuit

currents are required for only 250 microseconds or less, AC coupling can be satisfactorily employed in the VB drive part of the circuit.

The waveform at point A is determined by the DC amplifier which is in fact the X and P Adder. Its two inputs, the holding voltage -X and the pulse output from the Pulse Amplifier, are added together with a gain of -1 and appear at point A. The waveforms are shown in Fig. 12G. Adjustment of the variable resistor RG will change the galvanometer current for a particular drive voltage.

The actual details of the circuit are shown in Fig. 19. Here it is seen that tubes VA and VB are in fact each 2 double triodes connected in paralled. These are V12, V13 and V14, V15. 12AU7's are used for this purpose.

The X and P Adder is a Philbrick Operational Amplifier type K2-X. Bias is supplied by R4 and Pot. 1. The resistor R5, connected from the output of the K2-X to the +300 volts supply, ensures that this amplifier will give the ± 75 volts drive as well as supply the 15 volts bias required by the tubes V12 and V13. (See K2-X specifications, **page 65.**)

The AC amplifier is tube V11 - a 6AN8. The pentode section is a conventional RC coupled stage with a nominal gain of 100. The triode section is a cathode follower connected to the output of the amplifier. It is within the feedback loop of the amplifier which has a closed loop gain of -1. The cathode follower output of this stage was found to be necessary to deal with the grid current drawn by tubes V13, V14 on large drive amplitudes.

## THE TEST CIRCUIT

### i) Requirements

The signals required to operate the galvanometer positioning circuit are as follows: -

a) The holding voltage -X.

b) The change in holding voltage $|\Delta X|$.

c) A pulse of the same sign as $\Delta X$ to operate the P1 trigger circuit.

It was decided to test the response of the galvanometer for deflections from 0 to X and back again from X to 0. This simplified the circuitry required in that for any particular value of X, $|\Delta X|$ is now the same for both outward and inward movements of the galvanometer.

In order that the response of the galvanometer could be examined for a comparitively long time after its initial positioning movement, it was required that the time between movements should be variable between 1,000 and 10,000 microseconds. These times correspond to 100 and 1,000 separate movements per second respectively.

### ii) Method of Operation

The block diagram of the test circuit is shown in Fig.20. From this it can be seen that a square wave signal generator is used to drive the circuit. It triggers a monostable multivibrator which has a restoration time of about

3300 microseconds. For an input frequency of about 150 c/s, a square wave output of 120 volts amplitude is obtained from the multivibrator. This output performs two functions. Firstly it supplies the input for the P1 trigger circuit and secondly it operates a gate circuit. This gate has another input voltage which is $+|\Delta X|$. (In the test circuit $+|\Delta X|$ is a positive DC voltage). The output pulses from the gate are arranged to be $-|\Delta X|$ in amplitude and of the same duration as the multivibrator pulses.

For the test conditions, since $\Delta X = X$ then $-|\Delta X| = -X$ and thus the output from the gate is used for the holding voltage $-X$ in the deflection circuit.

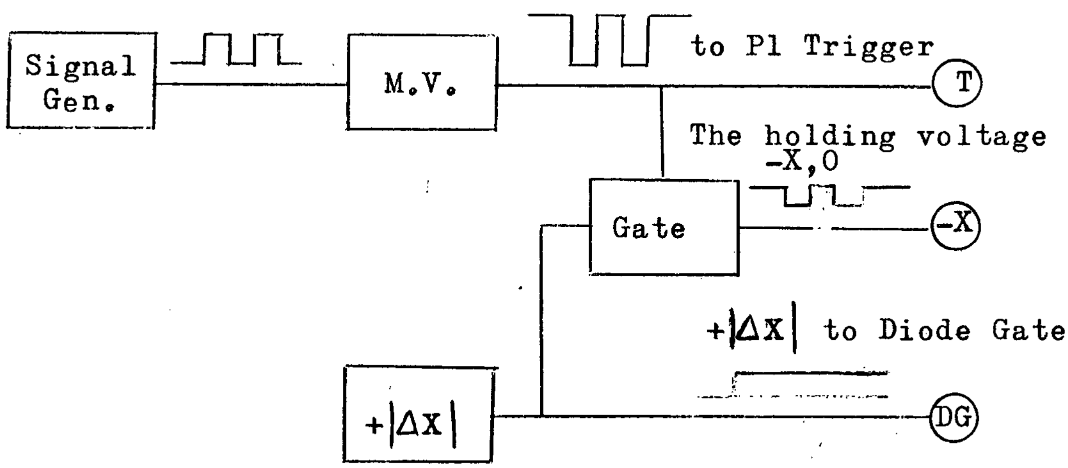



Fig. 20. The Block Diagram of the Test Circuit

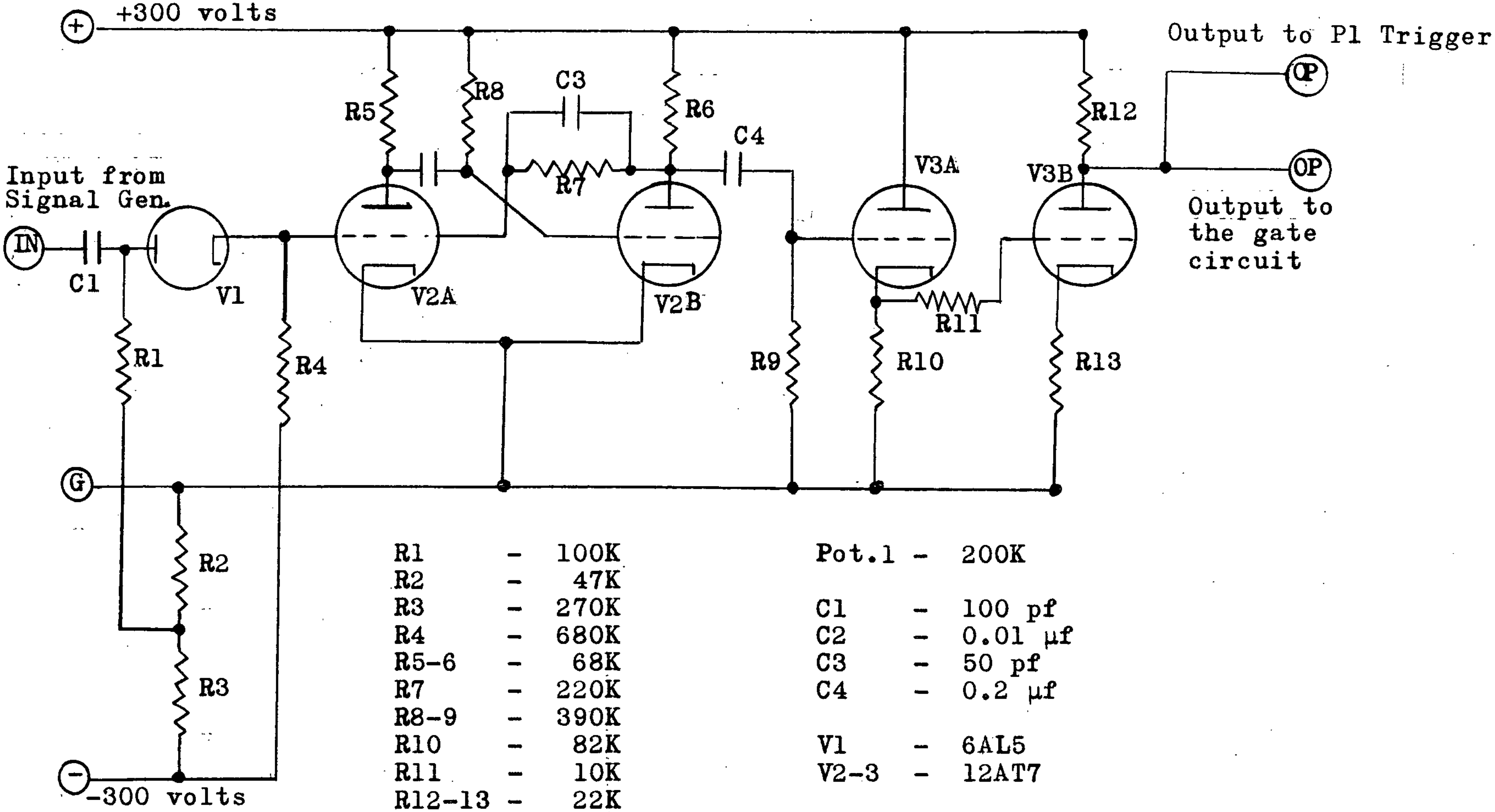
Circuit Details

The multivibrator Fig. 21.

The tube V2 - a 12AT7 double triode - is connected as a monostable multivibrator. It is triggered from positive pulses derived from a square wave of 50 volts amplitude applied to the IN terminal of the circuit. The output from tube V2 is a series of 200 volt positive going pulses, each of 3300 microseconds duration. The time interval between these pulses can be varied by changing the repetition rate of the input square wave. This interval can be reduced to 1000 microseconds or lower if desired. However, negative going pulses are required to operate the gate circuit, so the multivibrator signal is fed to an inverter circuit V3B via a cathode follower V3A. The cathode follower is necessary to avoid loading the plate circuit of tube V2B. The negative output pulses from the plate of V3B are 120 volts in amplitude and, of course, have the same duration as those from the multivibrator. From the output terminal they are applied to the IN terminal of the gate circuit Fig. 23 and also to the input of the P1 trigger circuit Fig. 13.

The duration of the multivibrator pulses is determined as follows: -

Since R8 is connected to the +300 volts supply, the restoration time for the monostable multivibrator is given




| | | |
|---|---|---|
| R1 | - | 100K |
| R2 | - | 47K |
| R3 | - | 270K |
| R4 | - | 680K |
| R5-6 | - | 68K |
| R7 | - | 220K |
| R8-9 | - | 390K |
| R10 | - | 82K |
| R11 | - | 10K |
| R12-13 | - | 22K |

| | | |
|---|---|---|
| Pot.1 | - | 200K |
| C1 | - | 100 pf |
| C2 | - | 0.01 µf |
| C3 | - | 50 pf |
| C4 | - | 0.2 µf |
| V1 | - | 6AL5 |
| V2-3 | - | 12AT7 |

Fig. 21. <u>The Test Circuit - Multivibrator Circuit Diagram</u>

approximately by

$$T = R8C3 \text{ Ln.} \left[ \frac{E_{bb} + (E_{bb} - E_b)}{(E_{bb} - E_b) + E_{co}} \right] \quad \text{secs.}$$

Where $E_{bb}$ is the plate supply voltage

$E_b$ is the quiescent plate voltage

$E_{co}$ is the cutoff voltage of the tube

Note that the quantity $(E_{bb}-E_b)$ is the voltage swing on the plate of V2A.

In this case $E_{bb}$ = 300 volts

$E_b$ = 50 volts

$E_{co}$ = -10 volts.

Substituting these and the values for R8 and C3 in the equation given shows that approximately T = 3250 microseconds. This checks out with the value found in practice which was 3300 microseconds.

The Gate Circuit (Fig. 23.)

The gate circuit used here comprises two K2-X Philbrick amplifiers referred to as K2-XA and K2-XB. These are depicted in the simplified diagram shown below, Fig. 22.

K2-XB is arranged as a DC feedback amplifier whose gain is adjusted to be -1 by means of Pot. 5. R7 and R8 together make up the input resistance to K2-XB. The input signal is applied to R7 and is the DC voltage $+|\Delta X|$. However, this voltage is not allowed to operate K2-XB because of the feedback action of K2-XA. Under no signal conditions, tube V1B is conducting and acts as the feedback resistor to K2-XA. K2-XA thus keeps the junction between R7 and R8 at zero volts. It is only when the tube V1B is cutoff by the negative going multivibrator pulses that the input grid of K2-XB is allowed to rise. This means that the multivibrator pulses operate the gate formed by these two Philbrick amplifiers so that the output from K2-XB is a train of negative pulses, the amplitude of which is $-|\Delta X|$ and the duration is 3300 microseconds, that of the multivibrator pulses.

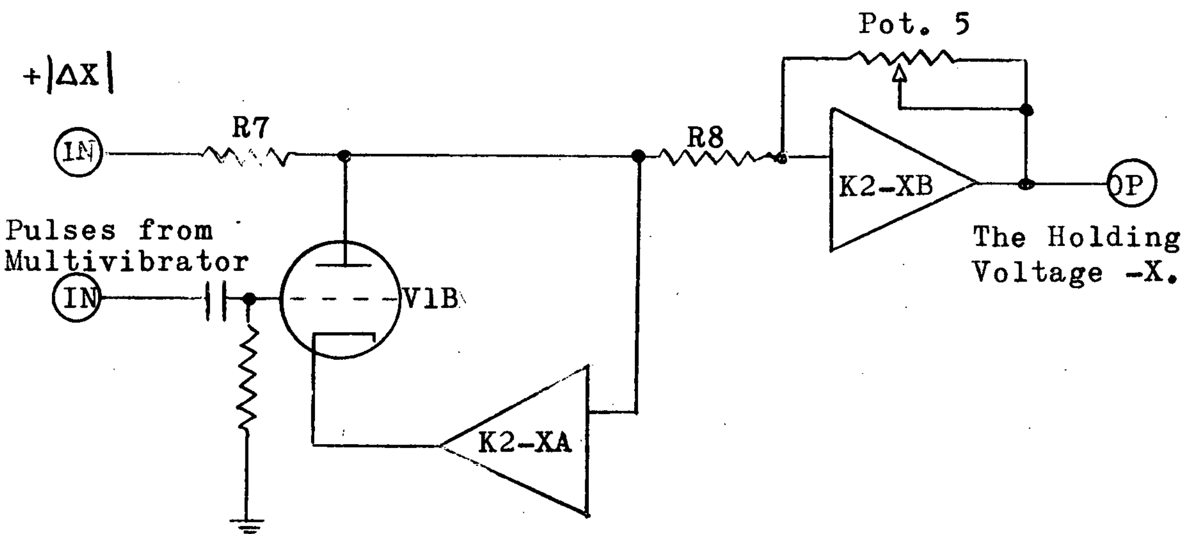
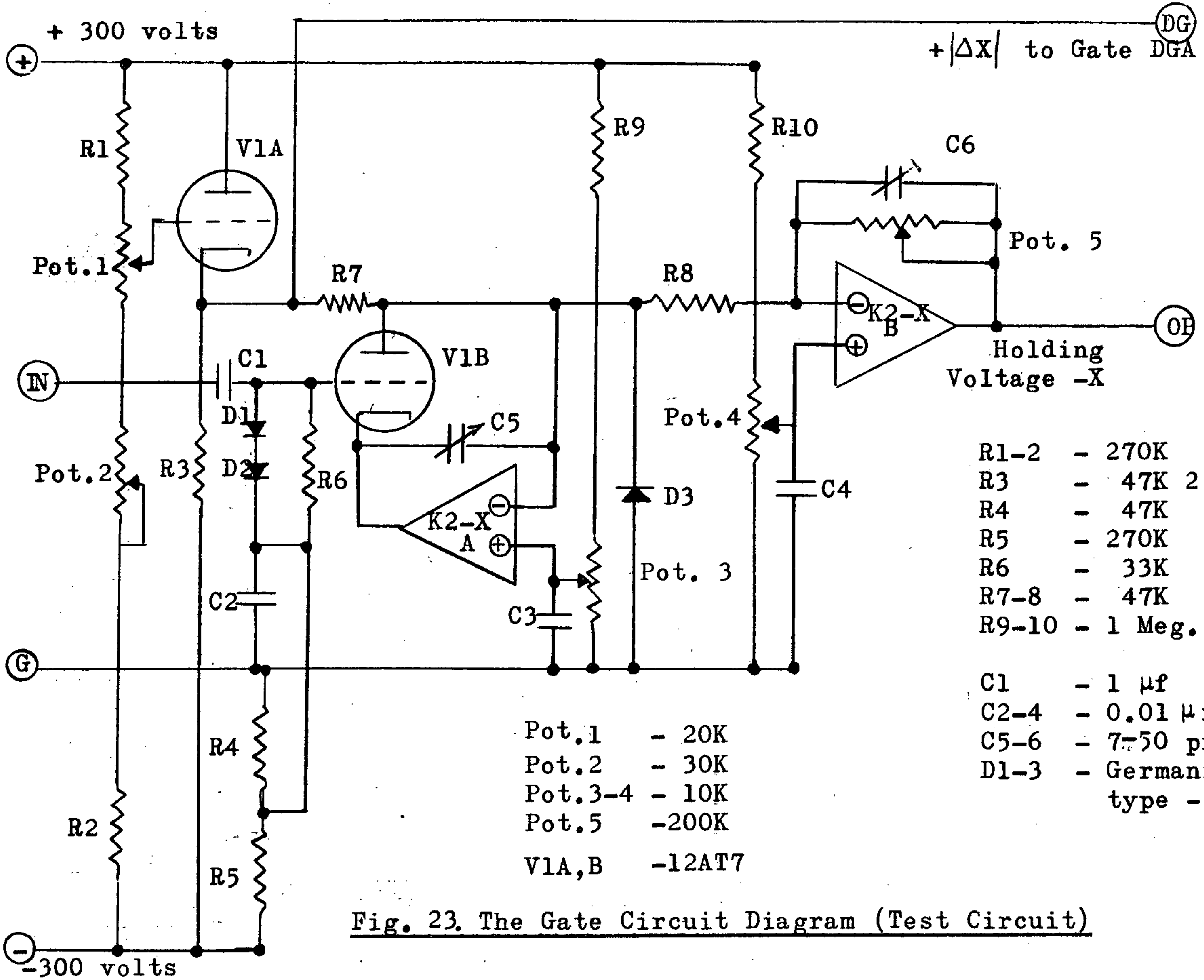



Fig. 22. The Gate Circuit - Simplified Diagram

Adjustment of Pot. 5 changes the gain of K2-XB which is normally kept at -1. This adjustment is made available in the test circuit in case it becomes necessary to change the voltage corresponding to X without affecting the amplitude of the phantastron pulses. The amplitude of the




| | | |
|---|---|---|
| Pot.1 | - | 20K |
| Pot.2 | - | 30K |
| Pot.3-4 | - | 10K |
| Pot.5 | - | 200K |
| V1A,B | - | 12AT7 |

| | | |
|---|---|---|
| R1-2 | - | 270K |
| R3 | - | 47K 2 watt |
| R4 | - | 47K |
| R5 | - | 270K |
| R6 | - | 33K |
| R7-8 | - | 47K |
| R9-10 | - | 1 Meg. |
| C1 | - | 1 μf |
| C2-4 | - | 0.01 μf |
| C5-6 | - | 7-50 pf (trimmer) |
| D1-3 | - | Germanium diodes type - 1N-191 |

Fig. 23. The Gate Circuit Diagram (Test Circuit)

phantastron pulses depends on the DC voltage from V1A in this circuit ($+|\Delta X|$).

The detailed circuit diagram is shown in Fig. 23. Tube V1A is a cathode follower the output of which is a DC voltage equal to $+|\Delta X|$. This voltage is taken to the diode gate DGA in the galvanometer positioning circuit via the terminal marked DG in Fig. 23. It also forms the input voltage to the Philbrick amplifier gate under discussion. $+|\Delta X|$ can be varied between 0 and 20 volts by adjustment of Pot. 1. Pot. 2 is adjusted so that at the lowest setting of Pot. 1 the voltage on V1A cathode is 0 volts.

The grid of tube V1B is held at about -45 volts by resistors R4 and R5. A negative voltage is used to reduce the size of the pulse necessary to cut off this tube.

Diodes D1 and D2 are connected across R6 to prevent any positive overshoot of the voltage on the grid of V1B. Diode D3 and capacitors C5 and C6 are also connected in the circuit to eliminate overshoot of the output waveform from K2-XB.

Bias for the Philbrick amplifiers is provided in the usual manner by resistor R9 and Pot. 3 for K2-XA and by R10 and Pot. 4 for K2-XB.

## THE RESULTS OF THE GALVANOMETER RESPONSE TESTS

The response of the galvanometer was examined for input signals of different pulse amplitude to holding voltage ratios (i.e. different values of K). The upper value for K is limited by considerations of accuracy and by the maximum pulse current which the galvanometer can accept. It was found that for values of K less than 4, the pulse lengths required were longer than the apparatus could supply - i.e. longer than 250 µsecs. For Values of K greater than 4, while the positioning time was reduced, the adjustment of the pulse lengths became critical and was subject to drift.

The best performance of the system was obtained for K = 4. The driving waveforms and the response curves of the galvanometer, for 4 different amplitudes are shown on pages 56 to 59. It was found that over all amplitudes of signal, for deflections from 0 to $X_{max}$, that the initial positioning time could be kept at 350 µsecs. This compares with 1800 µsecs for the response to a step input. In neither case can the beam be considered perfectly stationary until some time after the initial movement. In the case of the pulsed input this point is reached in a further 250 µsecs. The pulse lengths required to achieve these results are: P1 = 210 µsecs and P2 = 90 µsecs. In the photographs there is a slight difference between the pulse lengths for the outward and inward movements of the galvanometer.

However, it was found later that these times could be made equal without affecting the response waveforms.

With K = 6 the waveforms for maximum amplitude are shown on page 60. The initial positioning time here is 280 μsecs, but because the adjustment was very sensitive, this result could not be maintained over a long period of time. Also it was found impossible to eliminate a small overshoot which occurred at all amplitudes and meant that the total response was no better than for the case when K = 4. The duration of the pulses for K = 6 are P1 = 180 μsecs P2 = 80 μsecs, for both inward and outward directions of movement.

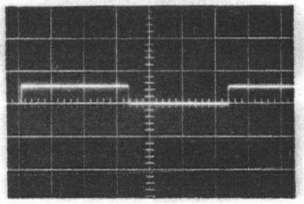
For all values of K the temperature of the galvanometer considerably affected the performance. With the arrangement used for the tests the lamp and the galvanometer were in the same compartment. Under these conditions the performance did not stabilize until some 2 hours after the apparatus was switched on and the temperature of the apparatus had been raised to a constant level by the heat from the lamp.

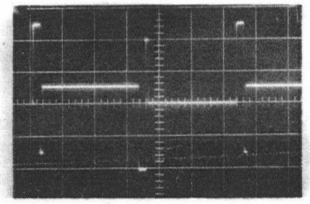
## Driving Waveforms and Galvanometer Response Photographs

SHEET 1. Taken for 16 mm. deflection of the galvanometer and K=4:1. Input voltage X = 15 volts producing a holding current of 16 mAs. Pulse amplitude 60 volts, producing a pulse current of 64 mAs.

Step Input (X only) Pulsed Input. Scales - per square.

Driving Waveforms.

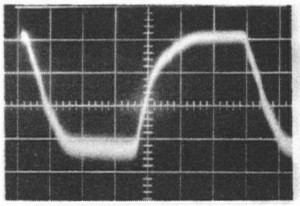


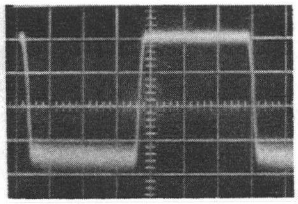


Vertical 30 volts.

Horizontal 1000μsecs.

Galvanometer Response. (P-M Output)





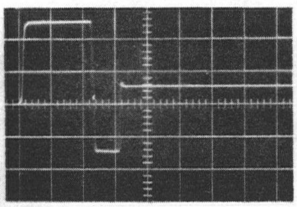
Vertical 1 volt.

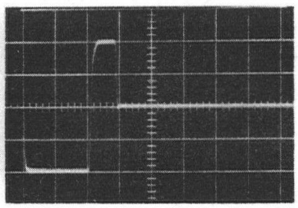
Horizontal 1000μsecs.

The photographs below are of the same Pulsed Input signal and the galvanometer response curves as above but with the time scale expanded 10 times - i.e. to 1 square = 100 μsecs.

The 0 to X Signal The X to 0 Signal

Driving Waveforms

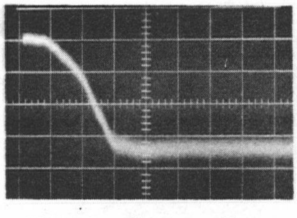


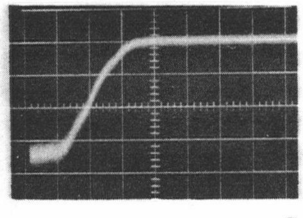


Vertical 30 volts.

Horizontal 100 μsecs.

Galvanometer Response. (P-M Output)





Vertical 1 volt.

Horizontal 100 μsecs.

Positioning Times: With Step Input . . . . . . . . 1300 μsecs.

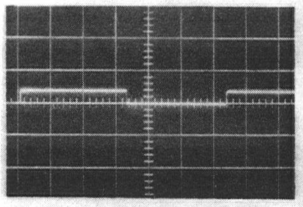
With Pulsed Input
(a) for the 0 to X Signal. 350 μsecs.
(b) for the X to 0 Signal. 350 μsecs.

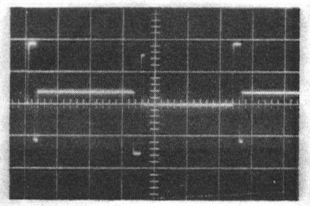
## Driving Waveforms and Galvanometer Response Photographs

SHEET 2. Taken for 12 mm. deflection of the galvanometer and K=4:1. Input voltage X = 11.25 volts producing a holding current of 12 mAs. Pulse amplitude 45 volts, producing a pulse current of 48 mAs.

Step Input (X only)    Pulsed Input.    Scales - per square.

Driving Waveforms

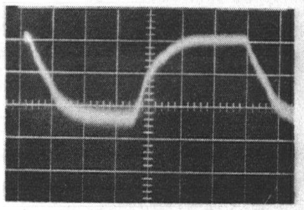


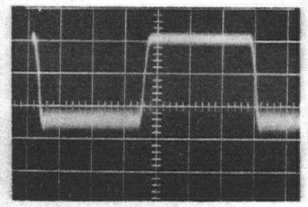


Vertical 30 volts.

Horizontal 1000 µsecs.

Galvanometer Response. (P-M Output)





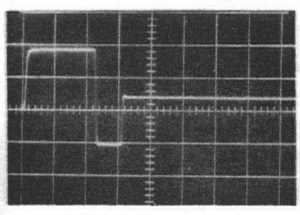
Vertical 1 volt.

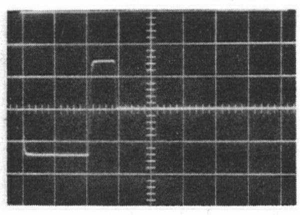
Horizontal 1000 µsecs.

The photographs below are of the same Pulsed Input signal and the galvanometer response curves as above but with the time scale expanded 10 times - i.e. to 1 square = 100 µsecs.

The 0 to X Signal    The X to 0 Signal

Driving Waveforms

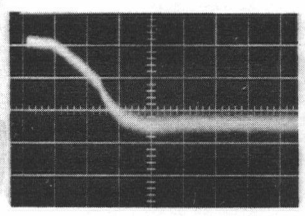


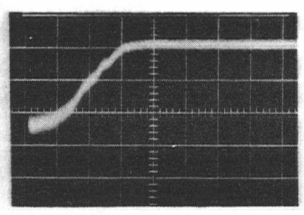


Vertical 30 volts.

Horizontal 100 µsecs.

Galvanometer Response. (P-M Output)





Vertical 1 volt.

Horizontal 100 µsecs.

Positioning Times: With Step Input . . . . . . . . . 1800 µsecs.

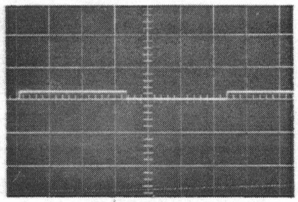
With Pulsed Input
(a) for the 0 to X Signal . 360 µsecs.
(b) for the X to 0 Signal . 350 µsecs.

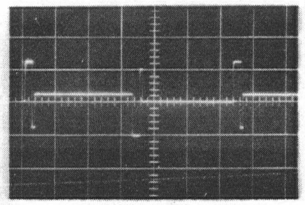
Driving Waveforms and Galvanometer Response Photographs

SHEET 3. Taken for 8 mm. deflection of the galvanometer and K=4:1. Input voltage X = 7.5 volts producing a holding current of 8 mAs. Pulse amplitude 30 volts, producing a pulse current of 32 mAs.

Step Input (X only)    Pulsed Input.    Scales - per square.

Driving Waveforms

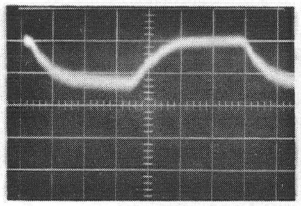


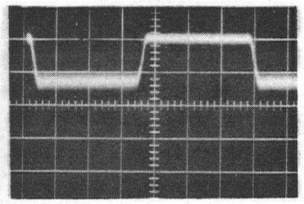


Vertical 30 volts.

Horizontal 1000 µsecs.

Galvanometer Response. (P-M Output)





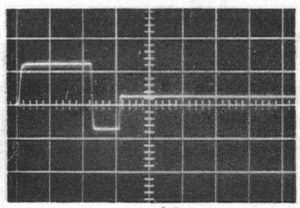
Vertical 1 volt.

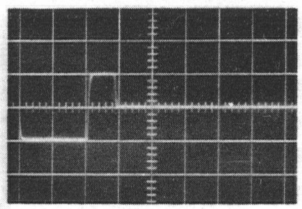
Horizontal 1000 µsecs.

The photographs below are of the same Pulsed Input signal and the galvanometer response curves as above but with the time scale expanded 10 times - i.e. to 1 square = 100 µsecs.

The 0 to X Signal    The X to 0 Signal

Driving Waveforms

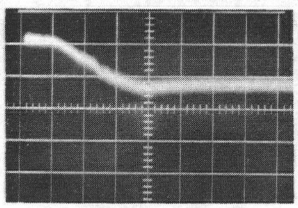


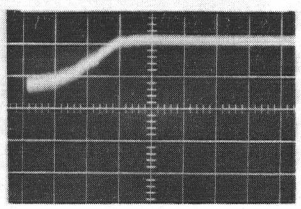


Vertical 30 volts.

Horizontal 100 µsecs.

Galvanometer Response (P-M Output)





Vertical 1 volt.

Horizontal 100 µsecs.

Positioning Times: With Step Input . . . . . . . . . 1800 µsecs.

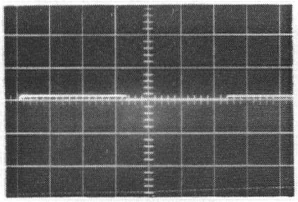
With Pulsed Input
(a) for the 0 to X Signal . 400 µsecs.
(b) for the X to 0 Signal . 300 µsecs.

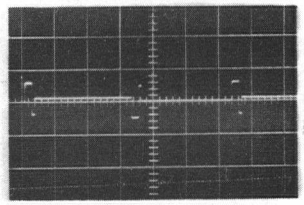
Driving Waveforms and Galvanometer Response Photographs

SHEET 4. Taken for 4 mm. deflection of the galvanometer and K=4:1. Input voltage X = 3.75 volts producing a holding current of 4 mAs. Pulse amplitude 15 volts, producing a pulse current of 16 mAs.

Step Input (X only) | Pulsed Input. | Scales - per square.

Driving Waveforms

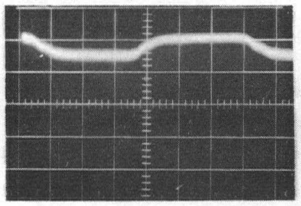


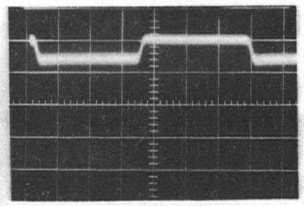


Vertical 30 volts.

Horizontal 1000 μsecs.

Galvanometer Response. (P-M Output)





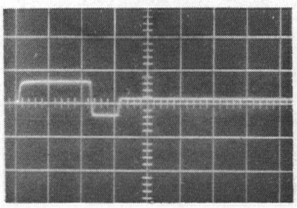
Vertical 1 volt.

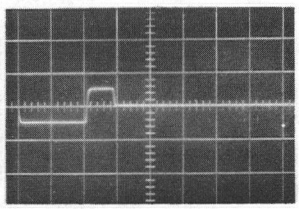
Horizontal 1000 μsecs.

The photographs below are of the same Pulsed Input signal and the galvanometer response curves as above but with the time scale expanded 10 times - i.e. to 1 square = 100 μsecs.

The 0 to X Signal | The X to 0 Signal

Driving Waveforms

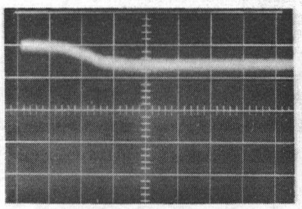


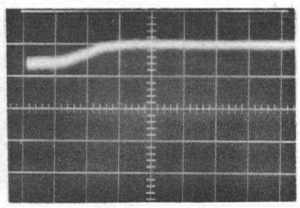


Vertical 30 volts.

Horizontal 100 μ secs.

Galvanometer Response (P-M Output)





Vertical 1 volt.

Horizontal 100 μsecs.

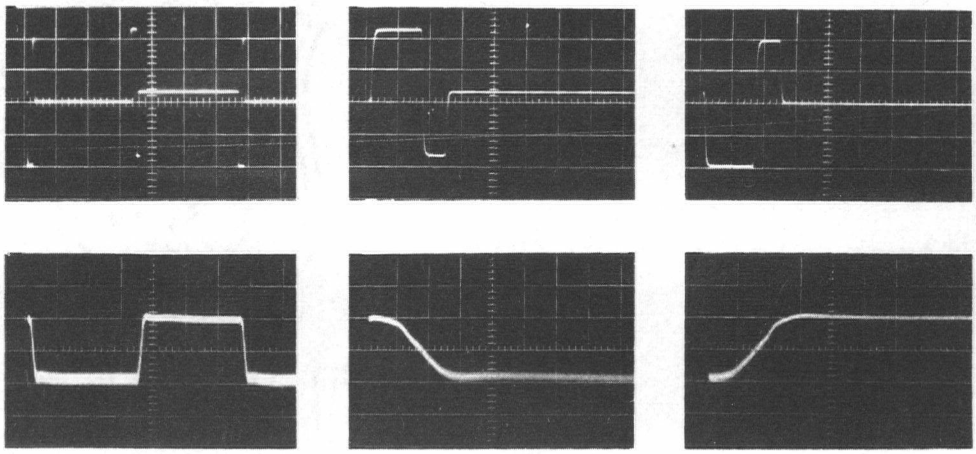
Positioning Times: With Step Input . . . . . . . . . 1500 μsecs.

With Pulsed Input
(a) for the 0 to X Signal . 350 μsecs.
(b) for the X to 0 Signal . 300 μsecs.

Driving Waveforms and Galvanometer Response Photographs

SHEET 5. Taken for 16 mm. deflection of the galvanometer and K=6:1. Input voltage X = 10 volts, producing a holding current of 16 mAs. Pulse amplitude 60 volts, producing a pulse current of 96 mAs.

| | The Complete Signal | The 0 to X Signal | The X to 0 Signal |
|---|---|---|---|
| Driving Waveforms | | | |
| Galvanometer Response (P-M Output) | | | |



Horizontal Scales per square: - 1000 μsecs. 100 μsecs. 100 μsecs.

Vertical Scales per square: -
for the Driving Waveforms ...... 30 volts
for the Galvanometer Response... 1 volt.

Duration of Pulses: Both P1 Pulses 160 μsecs.

Both P2 Pulses 90 μsecs.

Positioning Times: With Pulsed Output
(a) for the 0 to X Signal.. 300 μsecs.
(b) for the X to 0 Signal.. 280 μsecs.

## CONCLUSIONS

### i) An Analysis of the Results

When considering the galvanometer response, the figures show that the beam can be accurately positioned within the time for one frame of the function drum. With the present system, if the galvanometer were required to be positioned between frames, at least 500 μsecs would have to be allowed for the positioning time. This would leave 500 μsecs for generating the function.

From the galvanometer response times obtained in practise, it would appear that the effective value of the damping factor is considerably less than indicated by linear theory. The theoretical value of was computed from the natural frequency of oscillation $f_n$= 1000 c/s and the damped resonant frequency $f_d$= 325 c/s. They are related by the equations: -

$$\beta = 2\pi f_d = \sqrt{1 - \delta^2}\,\omega_n \qquad \ldots\ldots (1)$$

$$\text{and} \quad \alpha = \delta\omega_n \qquad \ldots\ldots (2)$$

From (1) $\delta = 0.85$

From (2) $\alpha = 0.85\omega_n$

From the results obtained in practise good correlation is obtained between theory and practise if $\alpha$ is taken as $\frac{1}{3}\delta\omega_n$ . This is an empirical result. No theoretical justification is possible because of the extreme speed of response and the complicated transient conditions in the damping fluid and the suspension of the coil. Using this value of $\alpha$ for a signal where K = 4 and where the time until the third step is applied, $t_2$ is 300 µsecs, the second step must theoretically be applied at $t_1$ = 220 µ secs. This compares with 210 µsecs obtained in practise.

For a signal where K = 6 and $t_2$ = 250 µsecs, theory indicates (for $\alpha = \frac{1}{3}\delta\omega_n$) that $t_1$ = 140 µsecs. In practise $t_1$ = 150 µsecs.

ii) Recommendations for Future Work

If a shorter positioning time is required, probably the most satisfactory means of accomplishing this would be by reducing the galvanometer damping. If this were done, however, trouble might be experienced in eliminating all overshoot. In this connection, it is possible that the slight movement remaining after the completion of the driving signal is due to movement of the damping fluid. Hence some other form of damping might be attempted - e.g. electrical damping.

Experimental results show that the pulses for both outward and inward movements have the same length. This means that 2 phantastrons can be made to operate the circuit instead of the 4 used at present. The proposed block diagram is shown in Fig. 24. Here it will be noted that the input signal requirements have been simplified. The trigger signal is now a positive pulse occurring whenever a new deflection is required.

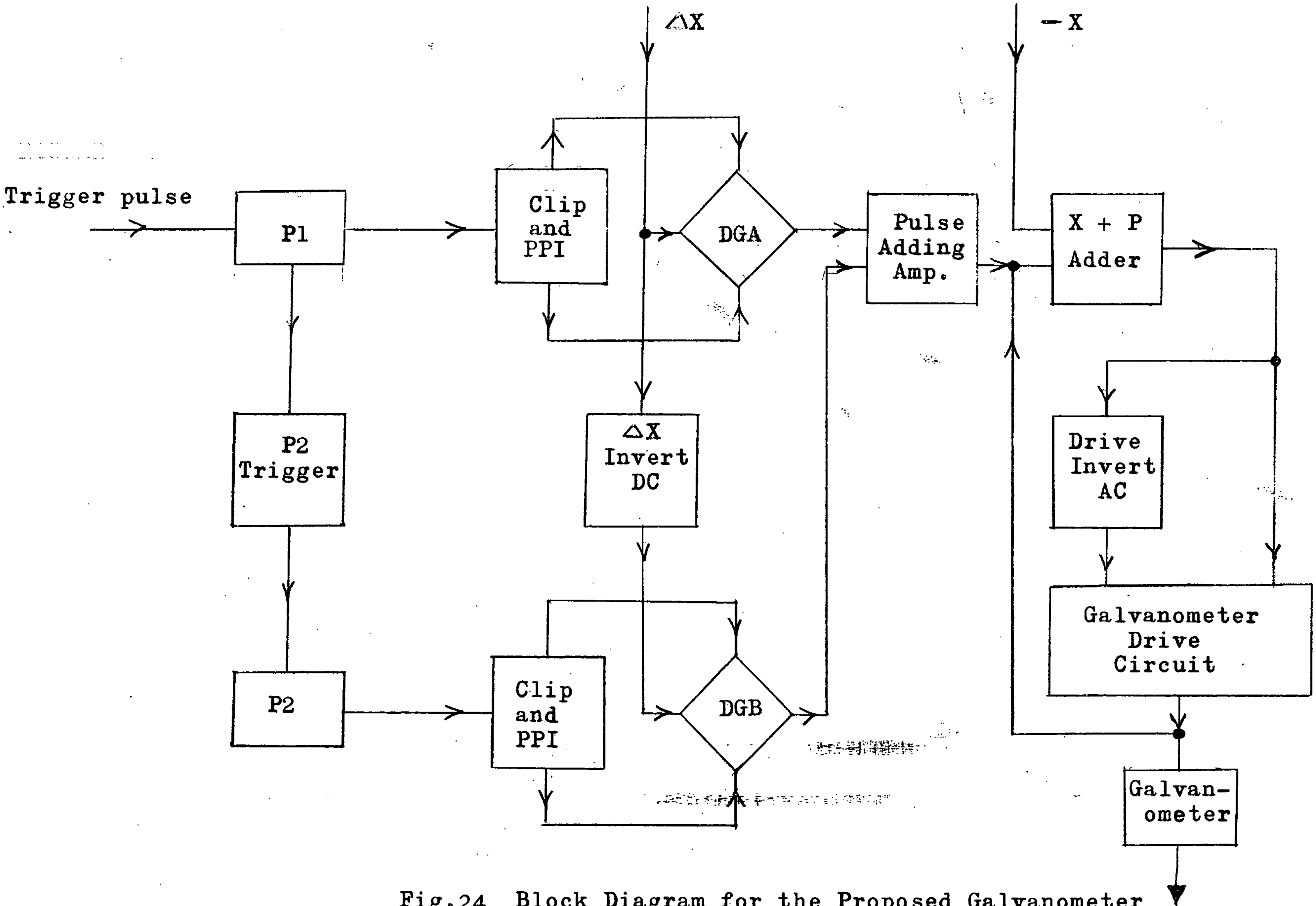



Fig. 24. Block Diagram for the Proposed Galvanometer Positioning Circuit

Its direction does not depend on the sign of $\Delta X$. The inputs to the two gates DGA and DGB are now $+\Delta X$ and $-\Delta X$ respectively. The $|\Delta X|$ signal is no longer required.

In order to prevent drift of the D.C. amplifiers from affecting the accuracy of function generation, the circuit must be arranged to correct this. This can be accomplished by means of one test function which will check the zero position of the galvanometer. A bias signal will be produced from this function to eliminate the zero error of the galvanometer each rotation of the drum.

Provided that errors due to drift are completely eliminated, the electrical signals can be made as accurate as desired. Thus the main source of error in the system will be due to the mechanical alignment of the frames on the drum. This part of the system will have to be very carefully engineered.

From the foregoing it can be concluded that the groundwork has been completed for the construction of an accurate and versatile method of function generation which satisfies the requirements laid out at the beginning of this thesis.

# APPENDIX

The Philbrick operational amplifier K2-X is a compact plug-in unit primarily intended for feedback operations. It features balanced differential inputs for versatility and minimum drift. Following are the general specifications:

Model K2-X Operational Amplifier

**GAIN**
30,000 DC, open-loop

POWER REQUIREMENTS
7.5 ma. at +300 VDC
5.2 ma. at -300 VDC
0.75 amp. at 6.3 V

INPUT IMPEDANCE
Above 100 Megohms

OUTPUT IMPEDANCE
Below 300 ohms open-loop; less than 0.2 ohms fully fed back

DRIFT RATE
5 millivolts per day referred to the input

VOLTAGE RANGE
-50 to +50 VDC for inputs (together)

-100 to +100 VDC for output (maximum)

INPUT CURRENT
Less than 0.1 micro-amp. for either input

OUTPUT CURRENT
-2ma. to +2 ma., driving 25K load from -50 to +50 VDC

INPUT BIAS
Positive input should operate 0.6 V high at balance (external bias)

RESPONSE
1 μsec. rise time with band width over 250 KC when used as an inverter

AUGMENTED POWER
100 K 2W resistor connected between output and -300 VDC supply. Drives 33K load over full voltage range ±100 volts

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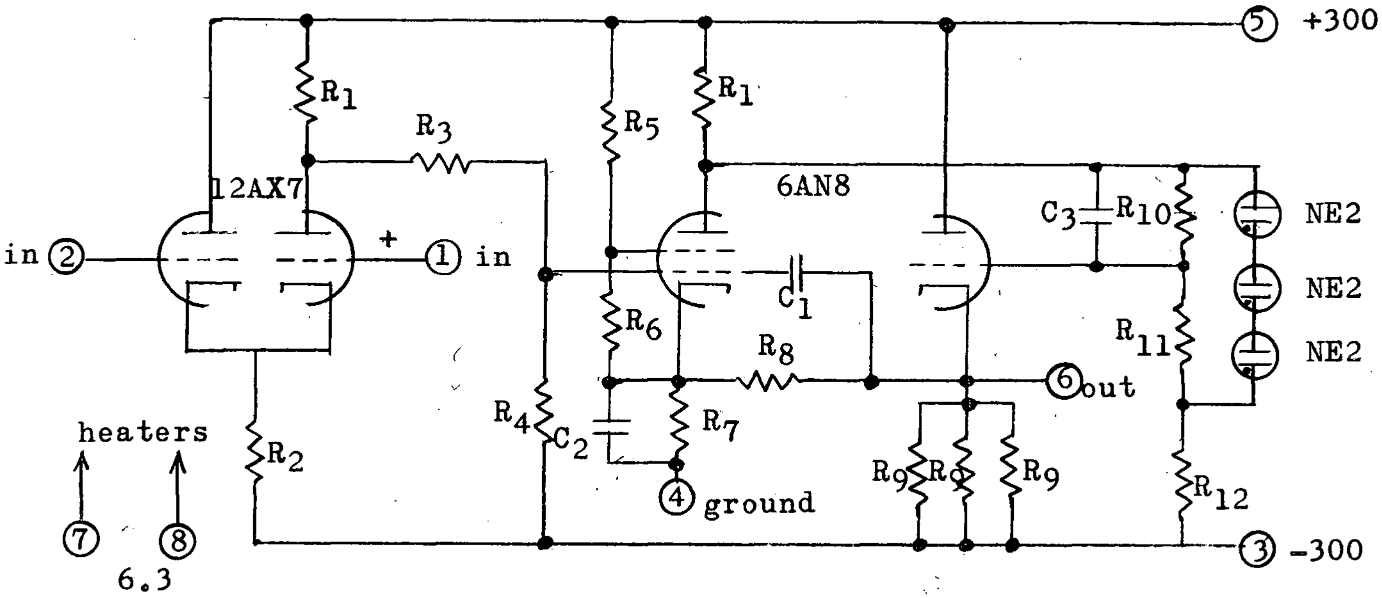
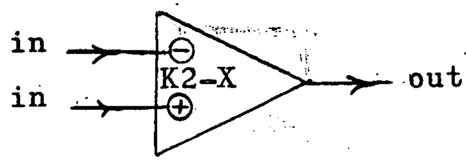



R$_1$ - 150 K.
R$_2$ - 150 K., 1 watt
R$_3$ - 470 K.
R$_4$ - 1 Meg.
R$_5$ - 180 K.
R$_6$ - 68 K.
R$_7$ - 2.2 K.
R$_8$ - 82 K.

R$_9$ - 220 K.
R$_{10}$ - 10 Meg.
R$_{11}$ - 1.5 Meg.
R$_{12}$ - 4.7 Meg.

C$_1$ - 15 pf.
C$_2$ - 5000 pf.
C$_3$ - 7.5 pf.




Symbol

Resistor tolerance - 5%

Fig. 25 Model K2-X Operational Amplifier.
George A. Philbrick Researches, Inc.

## BIBLIOGRAPHY


1. Korn, G.A. and Korn, T.M. Electronic Analogue Computers New York, McGraw-Hill, 1952.

2. Chance, Hughes, MacNichol, Sayre and Williams "Waveforms". New York McGraw-Hill, 1949 (M.I.T. Radiation Lab. Series, Vol. 19).

3. Hildebrand, B.P. A Sampling Type Function Generator. M.A.Sc. Thesis, University of British Columbia, April, 1956.

4. Fiorentino, J.S. Timing and Coincidence Circuitry for a Time-Sharing Analogue Function Generator. M.A.Sc. Thesis, University of British Columbia, April 1956.

5. Smith, Otto J.M. "Posicast Control of Damped Oscillatory Systems". Proceedings of the I.R.E., vol. 45, no. 9, pp. 1249 - 1255. Sept. 1957.

6. Edwards, C.M. "Precision Electronic Switching With Feedback Amplifiers". Proceedings of the I.R.E., vol. 44, no. 11, pp. 1613 - 1620, Nov. 1956.

7. Wass, C.A.A. Introduction to Electronic Analogue Computers. New York and London, McGraw-Hill, 1955.

8. Millman, J. and Puckett, T.H. "Accurate Linear Bidirectional Diode Gates". Proceedings of the I.R.E., vol. 43, pp. 27 - 37, Jan. 1955.

9. Williams and Moody. "Ranging Circuits, Linear Time Base Generators and Associated Circuits". Institute of Electrical Engineers Journal, vol. IIIA, Radio Location, 1946, pp. 1188 - 1198.

10. Jenkins, F.A. and White, H.E. Fundamentals of Optics. New York, McGraw-Hill, 1950.