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A NEW METHOD FOR GRAPHICAL REPRODUCTION
OF CATHODE-RAY OSCILLOGRAMS

by

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ABSTRACT

An automatic device for tracing the waveform of a repetitive oscilloscope pattern has been developed. The waveform is accurately reproduced and magnified by a conventional X-Y recorder. Because optical and pulse techniques are used the system is capable of reproducing signals displayed on even the fastest available oscilloscopes. When used with a high-frequency traveling-wave oscilloscope the method is applicable to phenomena in the millimicrosecond region and is capable of utilizing time resolution down to 0.1 mμ sec. Deflections as small as one micron may be detected. In addition to making oscilloscope measurements faster and more convenient, many of the sources of distortion normally encountered in oscilloscopes are eliminated.

I. INTRODUCTION

During the course of making measurements of the decay times of scintillations, a method was needed for accelerating the transcription of oscilloscope waveforms. After consideration of methods of reading photographic plates automatically, it was decided that a more satisfactory method would be one which would transcribe the pattern directly from the oscilloscope.

A previously described method for the X-Y plotting of oscilloscope displays was shown to be accurate for signal frequencies up to 10 kc.¹ Our need, however, was for a method which was workable in the millimicrosecond region and for this the optical null technique of the system to be described was devised. The present instrument has been in operation at this laboratory for several months in conjunction with a traveling-wave oscilloscope.² There is no limit to the degree to which the image may be magnified, but the inherent noise of this system limits the detectable deflection to about one micron, which is equivalent to one millivolt of signal at the deflection terminals.

II. PRINCIPLES OF OPERATION

Suppose that a thin plate containing a narrow slit is placed against the CRT face so that the slit is perpendicular to the X axis of the tube. As shown in Fig. 1, this plate also has a horizontal reference line marked across the slit. Now, by means of the "X pos." control of the CRO, let us move the trace across the slit, stopping at certain points along the time base. Also let us by some means cause the pen of an X-Y recorder to move in the X direction, stopping at these same points. At each point we will reposition the CRO trace vertically by means of the CRO's "Y pos." control so that that portion of the waveform visible through the slit will be aligned with the horizontal reference mark.

¹C. H. Hertz and E. Möller, Rev. Sci. Instr. 29, 611 (1958).

²Edgerton, Germeshausen and Grier, Type 2236.

The "Y pos." control varies a dc voltage on the Y plates of the CRT. At each point at which the beam is brought to a null as described above, there will be a different voltage on the Y plates. If this voltage or a voltage proportional to it is also fed to the Y input of the X-Y recorder and the pen is made to mark each point, there will be on the recorder chart a series of dots which, when connected, will give us a replica of the waveform.

Fig. 1. The basic method for the graphical reproduction of waveforms. Only a small section of the waveform W is seen through slit S in plate P.

With this technique the CRT is being used as a null detector and, since we are always reading from the same small point on the screen, any distortions caused by electron optics, non-uniformity of the glass, etc., are eliminated. Any non-linear characteristics of the CRT may be ignored. We could, if necessary, accurately draw a waveform which overloaded the CRT, i. e., one for which the deflected spot goes off the edge of the screen.

Several refinements can be added to this basic technique. We can install a device which will automatically and continuously keep the visible part of the trace at a null. This will allow us to have the waveform traverse the screen in a steady motion rather than in jumps from point to point. The same motor which drives a potentiometer to apply a

voltage ramp to the X plates to cause this motion can drive the recorder pen in its X direction. Thus the pen will draw the entire outline of the waveform. By varying the ratio between the X displacements of the waveform and of the pen, the drawing may be compressed or stretched according to the information desired. The time base can be calibrated by displaying the sine wave of a calibrated signal generator on the oscilloscope and having the pen draw it to the same scale as was used for drawing the waveform.

By varying the ratio of the voltage fed back to the Y plates to that fed into the Y input of the recorder, the maximum Y deflection in the drawing can be made full scale regardless of the height of the trace on the screen. In the design to be described, a pulse with a height of 2 mm on the screen can be magnified to cover the full 10-in. height of the recorder chart.

A practical design then would consist of (A) an optical device (the "perceiver") that views a narrow region in the center of the CRT screen as the waveform is moved across it in the X direction and senses any failure of the waveform to pass through null in this region, (B) an electronic circuit (the "restorer") that converts the information from the perceiver into a voltage that restores the beam to null and causes a proportional Y displacement of the recording pen, and (C) a device (the "scanner") that automatically moves the waveform and the recording pen synchronously in the X direction.

III. DESCRIPTION OF SYSTEM

A. The Perceiver.

As shown in Fig. 2, fastened to the front of the CRO chassis is a light-tight box containing the detecting system known as the "perceiver". The perceiver comprises a lens that focuses a magnified image of the waveform on a vertical slit S 0.016 inch wide in metal plate P, and a pair of multiplier phototubes whose combined signal indicates whether the element of waveform crossing the slit at each instant is above, below, or on the null position established by the

Fig. 2. The spatial arrangement of the lens L, slit S, mirror assembly M, and the photomultiplier tubes PM-1 and PM-2 with respect to the traveling-wave cathode-ray tube, and a block diagram of the electronic and electrical circuits of the system.

edge of the aluminized glass wedge. The light passing through the slit and falling on the wedge is reflected into either or both of the phototubes PM-1 and PM-2. By using the difference between the outputs of the phototubes as a signal, a null will be reached only when the beam is being split by the knife-edge. The mirror assembly M, which includes the wedge and the two mirrors on each side of it, is adjustable vertically so that the recorder pen may be zeroed at the appropriate point on the chart.

Note that since the CRO is sweeping repetitively, bursts of

light fall on the wedge and the outputs of the phototubes are pulses. The use of pulse techniques is absolutely necessary when working with short resolving times and low repetition rates. When this system is used with the fastest sweep of the EG&G oscilloscope, the spot is over the slit for only 2×10^{-10} seconds and the photoelectric signal is only a few hundred electrons per pulse. Such pulses are readily discriminated from noise, but the average current would be lost in the dark current of the phototube.

The phototubes used in the system are Dumont 6292's wired as usual and operated at 1150 volts. Their signals are fed into individual 6AK5 cathode followers (not shown in Fig. 2) which in turn feed the "restorer" circuits.

The perceiver box also includes a periscope and a hinged mirror which can intercept the beam between L and P to allow visual observation of the CRO face.

B. The Restorer.

Unequal pulse heights from the two channels in the perceiver indicate an off-null condition. The restorer uses this information to restore the image to a null position. This unit is contained on a single chassis and consists of two independent pulse amplifiers (one for each channel), an integrator consisting of a push-pull diode pump, a push-pull dc amplifier, and two power supplies for these units.

1. Pulse Amplifiers

These two units are identical but their connections to the integrator are in opposition. The circuit diagram is shown in Fig. 3. The purpose of the pulse amplifier is to convert the approximately 0.4-v pulse from the perceiver to a pulse of about 100 v in amplitude. Tubes V_1 , V_2 and V_{3A} form a standard ring-of-three feedback loop having a rise time of approximately 1.7 μ sec. Tube V_{3B} is a cathode follower serving to isolate the pulse amplifier from the following circuits. The measured gain of this amplifier is about 250. It should be noted that the input pulses are negative, while the output pulses are positive.

Fig. 3. Circuit diagram of the pulse amplifiers. Two such amplifiers are used with signals to the integrator in opposition.

Saturation of the amplifier will occur when V_{3A} is cut off. This undesirable condition is observed as a flattening of the top of the output pulse. P_2 is an oscilloscope terminal for the viewing of this pulse. The power supplied to the 6AK5 cathode follower in the receiver is filtered by $R_{19} C_{10}$.

2. Integrator

This unit uses the pulses from the two channels to produce a dc restoring voltage. This voltage is later amplified and fed to the vertical deflection system of the oscilloscope. Figure 4 shows the circuit diagram combining the integrator and dc amplifier. The integrator consists of the components C_{11} , C_{12} , V_4 , V_5 and one of the condensers $C_{13}-C_{16}$.

Since the operation of this circuit is complicated by the presence of feedback from the amplifier to the bottom of capacitors

$C_{13}-C_{16}$, we will first explain the operation as if this feedback were absent. Assume (a) that capacitors C_{17} and C_{18} are shorted, (b) that the balance speed selector S_1 (which adjusts the rate at which the null is approached) connects integrating capacitor C_{14} into the circuit, (c) that pulses of approximately 100 v amplitude are entering channel No. 1 but no pulses are in channel No. 2, (d) that V_c , the voltage across C_{14} , is initially equal to zero. Let us express all voltages relative to the bottom of C_{14} . Now the plate of V_{4B} will be at zero potential. The cathode of V_{4A} is biased at 13.7 volts positive from resistor string $R_{20}-R_{24}$. The potential of the plate of V_{4A} (and the cathode of V_{4B}) is indeterminate, but assume it to be initially zero.

As the pulse through coupling capacitor C_{11} starts to rise positively, V_{4B} will immediately block. When the plate of V_{4A} reaches +13.7 v, that diode will conduct, clamping the right-hand side of C_{11} at 13.7 v. As its left-hand side rises, C_{11} is charged accordingly. Since the entire circuit of the integrator and dc amplifier is floating, a ground return for the charging of C_{11} is provided by C_{19} . When the peak of the pulse is reached, C_{11} will be charged to $(V_p - 13.7v)$, V_p being the peak voltage of the pulse. As soon as the pulse begins to fall, V_{4A} blocks. When the pulse has fallen 13.7 volts from its peak value, the voltage across V_{4B} will be zero and it will begin to conduct. Now the negative charge on C_{11} is discharged into C_{14} . Since the latter is larger, it will develop only a small voltage, even when all the charge on C_{11} has been shared with it. When the pulse has returned to zero, both the plate and cathode of V_{4B} will be below zero potential only by the amount due to the charge on C_{14} . Each subsequent pulse will repeat the cycle of the first, except that each time the cathode and anode of V_{4B} will be left at a slightly more negative potential. This increasingly negative potential of the cathode of V_{4B} will in effect increase the bias on V_{4A} , so that C_{11} will charge only to $V_p - (13.7 - V_c)$ where V_c is the voltage across C_{14} . Therefore, the amount of charge delivered to C_{14} by each pulse is slightly

dependent upon the charge already on C_{14} , becoming less as that charge increases. The voltage on C_{14} is the signal which, after amplification, drives the Y axis of the recorder and restores the image in the perceiver to the null position. As we shall see, it is desirable that the charge delivered to C_{14} be relatively independent of the charge already on it. This dictates a small change in the voltage across C_{14} . But in order to override drifts at the input of the dc amplifier, we desire to develop a large signal on C_{14} . These two conflicting requirements are reconciled by the use of feedback to the bottom of C_{14} .

The operation of V_5 on pulses from channel No. 2 can be traced in a manner analogous to that indicated above for channel No. 1. One difference is that the connections of V_5 are reversed, and the bias

Fig. 4. Circuit diagram of the integrator and dc amplifier. The integrator is considered as consisting of C_{11} , C_{12} , V_4 , V_5 and $C_{13}-C_{16}$. In addition to these circuits the restorer includes two pulse amplifiers (Fig. 3).

developed by R_{22} is negative. Now coupling capacitor C_{12} is charged through V_{5A} from C_{14} and is discharged through V_{5B} . Consequently these pulses subtract electrons from C_{14} . Otherwise, the operation is identical to that of V_4 . When the voltage across C_{14} is zero, C_{12} is charged to $(V_p - 13.7 \text{ v})$, but when a negative charge appears on C_{14} this acts to reduce the bias developed by R_{22} , so that a positive charge on C_{14} tends to oppose the operation of channel No. 1. In the circuit described here, the voltage at the input to the grid of V_{6A} changes by 0.5 v in going from no signal to full-scale signal. This means that for 100-volt pulses, C_{11} and C_{12} will be charged to 86.3 v at zero signal, while at full scale C_{11} will be charged to 85.8 v and C_{12} will be charged to 86.8 v. Therefore, at full-scale signal, the image will have to move off the knife edge a small amount in order to equalize the effective pulse heights and stabilize the charge on C_{14} . This error has been measured to correspond to approximately one millivolt error in signal amplitude at the oscilloscope terminals. A pulse of 2 volts amplitude would be too small at the peak by 0.05%. This error is small, and furthermore since it is proportional to signal amplitude it will only shrink the pulse and will not change its shape. Therefore, we believe that its distortion of the pulse is negligible.

3. DC Amplifier

In our work, a logarithmic plot of a scintillation pulse is usually more useful than a linear plot and therefore a log-converter is connected between the dc amplifier and the X-Y recorder. The amplifier, then, was designed to provide the output of 135 v necessary to drive the log circuit. A simpler amplifier might be used if only linear plots were desired.

The restoring voltage on C_{14} is fed into V_{6A} . Twin triode V_6 is a balanced dc amplifier with a common cathode resistor. The effect of the latter is to produce a signal in V_{6B} which is opposite to that of V_{6A} , and to prevent cathode degeneration of the signal. The push-pull plate signals are fed into

the high- μ triodes of V_7 , the operation of which is similar to that of V_6 . Beside feeding the output amplifiers, V_{7B} provides feedback to the bottom of C_{14} . The gain to the feedback point is about 26, so that when the grid potential of V_{6A} rises 0.5 v, the bottom of C_{14} falls 13 v, and thereby produces a 13.5 v decrease across C_{14} . Drifts in V_{6A} are fed back, so that an effective drift of 0.1 v at the grid of V_{6A} is equivalent to about 0.6% of the full-scale signal. Without feedback, such a drift would be equivalent to 20% of full scale. The use of feedback limits the drift in the amplifier zero after warm-up to about 0.1% of full scale.

The network $R_{46}R_{47}C_{21}$ in the push-pull output of V_8 was found necessary to remove 60-cycle hum from the signal. Its time constant should be as short as can be tolerated from the point of view of the 60-cycle hum, since it introduces a time lag in the restoring voltage.

The output of the amplifier is a push-pull signal from the cathode followers V_9 and V_{10} . This signal is fed directly to our log-converter. Shown in the lower right corner of the diagram is the attenuator to which we may switch when a linear plot is to be made. This same signal feeds the vertical deflection plates of the oscilloscope to restore the observed element of the waveform to zero.

Between the cathode followers and the Y plate terminals P_6 and P_7 we find first the "Amp. Short" switch S_3 . Through use of this switch the recorder can be set to zero independently of the amplifier zero. The network $R_{53}-R_{56}$ provides a means for varying the fraction of the amplifier output being fed to the oscilloscope. The setting of R_{56} will determine the ratio of the height of the recorder drawing to the size of the oscilloscope display. This "peak height" adjustment allows one to obtain full-scale recorder drawings of displays ranging from 2 to 7 mm in height.

It should be noted, however, that as the peak height is increased

(by decreasing R_{56}) the rate of generation of restoring voltage is reduced. This is equivalent to increasing the capacitance of the integrating condenser, so the optimum setting of the balance speed selector will depend upon the setting of the peak-height control.

The network R_{57} - R_{60} further attenuates the restoring voltage and provides the only dc ground reference in the system. In this way, the output to the CRO is always balanced with respect to ground. Resistors R_{57} and R_{58} also prevent the tilt voltage, which is fed in from the scanner via P8, from being shorted out by the relatively low impedance of R_{55} when R_{56} is at minimum resistance. The tilt voltage is a small voltage which compensates for any tilt which may be observed in the baseline as it is drawn by the recorder. This voltage is directly proportional to the X-position voltage so its effect is to rotate or "tilt" the baseline.

Network R_{61} C_{22} R_{62} C_{23} filters out a ripple of several volts found between the output and ground. There is a similar network in the output to the X-Y recorder. As in the case of the output of V_8 mentioned above, these filter networks delay the restoring voltage in reaching the output terminals. It is believed that this ripple comes in through capacitive coupling between the windings of the power transformer in the floating power supply since the supply output is adequately filtered. The use of a power transformer having a Faraday shield may reduce or eliminate the ripple. The elimination of these output filter networks would, of course, improve the instrument by allowing faster response of the recorder.

Resistors R_{63} and R_{64} isolate the signal which comes in through P6 and P7 from the low impedance presented by C_{22} and C_{23} , thereby causing it to be absorbed by R_{65} and R_{66} through paths provided by C_{24} and C_{25} . The values of R_{65} and R_{66} are determined by the input impedance of the oscilloscope. The capacitors C_{24} and C_{25} prevent the dc signal from being shorted

out by the low impedances of R_{65} and R_{66} .

Switch S_1 provides for the selection of one of four capacitors for use as the integrating capacitor, thereby controlling the rate at which a correction voltage is developed for any given unbalance of the pulses in channels 1 and 2. Use of larger capacitances is desirable for averaging out the statistical fluctuations inherent in the scintillation pulses. Furthermore, too small a capacitor may cause the restorer to over-correct and consequently "hunt". This effect is exaggerated by the lags produced by the earlier mentioned filters.

Control R_{41} normally is used to adjust the zero of the amplifier during operation but R_{24} has the same function. When zeroing the amplifier, S_1 is thrown to the "test" position.

Switch S_2 enables several important measurements to be made. When a potentiometer is plugged into P9, the use of S_2 enables one to put this potentiometer in the circuit at any one of three points. In position "F" the potentiometer may be placed across C_{13} (with S_1 appropriately adjusted). In this way, the potentiometer simulates a voltage across the integrating condenser. Alternatively, the potentiometer may be replaced by a source of voltage variable between 0 and 15 volts. The latter may be used to drive the amplifier over its full range. In position "G", the potentiometer is placed between the two grids of V_6 . This connection enables one to measure the internal gain of the amplifier (with S_1 appropriately adjusted). Finally, with S_2 in position "O", the potentiometer is placed in series with one of the leads to the oscilloscope. It may be used to calibrate the recorder in terms of the signal voltage or for other useful purposes.

C. The Scanner.

The purpose of this section is to provide the voltage ramps to move the pattern across the face of the CRO and at the same time to move the

recorder pen in its X direction. These two voltages must be exactly proportional to each other and must change in perfect synchronism.

Figure 5 shows the basic circuit for distributing the voltages. Across the power supply PS-3 are two resistance strings. The uni-directional sawtooth voltage for the recorder is developed in R_6 in one string, while R_3 in the other string performs a similar function for the X deflection system of the CRO. These potentiometers are connected to a common shaft which extends through the front panel, permitting manual scanning. For automatic operation a pulley on the shaft is driven (through a rubber belt, a clutch and a Metron variable speed changer³) by a small Bodine motor internally geared for a motor shaft speed of 60 rpm.⁴ The clutch and speed changer are controlled from the front panel. Note that no particular pains need be taken to regulate the speed or to eliminate slippage as long as the shafts of R_6 and R_3 are firmly connected and therefore synchronized. Any small variations in speed will not distort the waveform unless such variations increase the scanning speed beyond that which the recorder can follow.

The "Recorder Adj." control, R_5 , adjusts the voltage that may be developed across R_6 so that the full X scan of the recorder will match the full excursion of R_6 and R_3 . By varying the voltage gradient across R_3 , the width control R_2 actually varies the rate of travel of the waveform on the oscilloscope with respect to the X travel of the recorder pen. If the waveform moves at a higher relative rate, the recorder drawing will be compressed, since a longer section of the time base will have passed the slit of the perceiver in the time that the recorder takes to make its full excursion. Conversely, if the speed of the waveform is lower, the drawing will be expanded or "magnified" in the X direction.

³Type 3B-6A-45, Metron Instrument Co., Denver, Colorado.

⁴Type KY6-23, 60 rpm, Bodine Electric Co., Chicago 12, Illinois.

Fig. 5. Circuit diagram of the "Scanner". Not included is the wiring of the motor which drives R_6 and R_3 .

A separate X voltage is supplied by a power supply PS-4 and potentiometer R_{12} . This enables one to begin the scan at any point along the time base.

To rotate or tilt the base line, as mentioned earlier, a small voltage proportional to the scanning voltage is provided by R_{19} . As are all potentiometers on this chassis, R_{19} is a ten-turn helipot for smoothness of control.

The power supplies PS-3 and PS-4 are floating and the type of 60-cycle ripple discussed in the dc amplifier section was also found in the outputs of this circuit. Networks $R_7R_8R_9R_{10}$, $C_1C_2C_3C_4$ and $R_{13}R_{14}R_{15}R_{16}$, $C_5C_6C_7C_8$ serve to filter the ripple.

The only ground reference for this circuit is through P3 from the restorer. Like the voltages fed to the Y deflection plates, those fed to the X plates are balanced with respect to ground.

IV. PERFORMANCE

A comparison of a photograph of a fast pulse with the instrument's drawing of the same pulse is shown in Fig. 6. The height of the pulse as displayed on the oscilloscope screen was 4 mm while the height of the drawing is 10 in. The drawing is actually five superimposed tracings to show the system's ability to reproduce a waveform consistently.

The resolution of the instrument is determined by the width of the slit in the perceiver. This slit should be as narrow as is consistent with a high signal-to-noise ratio in the output of the phototubes. The limit of closure of the slit then depends upon the amount of light available from the CRT screen and on the speed of the lens used between the screen and the slit. With the fastest sweep on the EG & G oscilloscope and an $f/2.8$ lens, a resolution of 0.1 μsec is possible.

To obtain accurate tracings of rapidly changing waveforms, the operator must also take into consideration the delay of the restoring voltage by the hum-filtering networks in the dc amplifier. For example, if the scanning speed were too fast for a given pattern the drawing of a very steep section would be too far to the right as well as distorted. Settings of the "Width", "Speed Selector" and "Peak Height" controls will have a bearing on the choice of a scanning speed. One can always check the accuracy of a drawing by point-to-point manual scanning.

In practice, the sine wave output of a calibrated signal generator is drawn along the bottom of the waveform record and measurements of the signal are easily and quickly made.

As has been pointed out, this system was designed for a specific oscilloscope but only minor modifications should be necessary to adapt it to

Fig. 6. A comparison between a photograph of a fast pulse and the corresponding drawing.

other makes and types.

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