Recent Developments in the Cathode-Ray Oscilloscope

JACK E. DAY

Engineering Department, Tektronix, Inc., Portland, Oregon

I. Introduction

A. General

The development and improvement of the cathode-ray oscilloscope encompasses a number of problems that are not strictly circuit-design exercises. Indeed, most of the problems that are crucial to the expansion of performance of this instrument are not technical *design* problems at all, but rather can be called technical *decision* problems. (As examples, what performance range should an instrument have? What concessions should be made to serviceability in the equipment? How can the reliability be improved without sacrificing the performance? How should the front panel controls be arranged?) Consequently, the solution of these problems involves questions of design philosophy, manufacturing techniques and capabilities, and user requirements and psychology. These questions, when answered, determine the "boundary conditions" and therefore the circuit designs which may be considered. It may be that this "performance area" will be handled adequately by existing techniques, and the design problem then becomes one of properly combining these techniques in the most efficient configuration to handle the job. More often (it is to be hoped!) these "boundary conditions" delineate areas which are not covered by existing methods, and thus require development and invention. In this way, the whole electronic art is advanced.

1. Selection of Performance Characteristics. "What characteristics should an oscilloscope have?"

If that question were to be asked of a number of oscilloscope users, probably as many answers would be received as persons questioned. However, ask the man who sells oscilloscopes, who deals with many users day in and day out, and who must answer their requests for specific equipment. Most likely he has a "dream" chart in his briefcase and requires little encouragement to talk about it. It might look like the following:

Bandwidth: Direct current—10,000 Mc (or some higher frequency) with frequency "roll-off" controls to permit any lesser desired bandwidth.

Sensitivity: Theoretical maximum at any bandwidth.

Input Characteristics: Infinite resistance, shunted by zero capacitance.

Sweep Ranges: 20 min to 0.2 mμ.

Stability: Absolutely stable; no drift, no gain changes, no operational failures—ever.

Writing Rate: Will display (and preserve until erased) single transients at the fastest sweep rate.

Flexibility: Signal and sweep channels can be added to provide as many simultaneous traces as desired. Amplifiers can be substituted for sweeps when desired.

Operational Simplicity: Has "autopilot" feature which anticipates conscious desires and unrealized needs of the user, eliminating the need for controls.

Size: The physical size determined by the dimensions of the indicator chosen; any size display is available at the customers' discretion.

It will be recognized that the above combination of characteristics is not only unlikely, but with present-day techniques, impossible. However, it is interesting to note that individually many of the specifications are possible and some are already obtainable.

This tongue-in-cheek illustration serves to point up the fundamental problem the circuit designer has to face—the necessity for compromise. In every art, success comes from knowing accurately the limits of each element, perceiving the complex interrelations of all the constituent parts, and then choosing wisely, accentuating some, diminishing others, until the optimum design for a particular need is produced.

Figure 1 illustrates a few of the elements of give-and-take in oscilloscope design. The important thing to note is that the improvement of one characteristic, say, bandwidth, normally requires the deterioration of one or more of the other characteristics, such as deflection scan, linearity, gain stability, etc. Consequently, the most useful design concepts are those which permit the extension of some particular parameter without the sacrifice of any other. While a few such principles have evolved in recent years, much of the progress in contemporary oscilloscopes has been achieved by the fine art of compromise—by the striking of a more useful balance of characteristics rather than by creating completely new concepts.

During the past decade, for example, there have been only a few major innovations in the basic elements comprising the oscilloscope. Instead, designers of the laboratory-type cathode-ray oscilloscope have concentrated primarily on minutiae in striving for technical perfection of their products. Nevertheless, a comparison between nearly any of the current high-performance instruments and one produced ten years ago would show an almost astounding advancement in nearly every aspect of design —physical, mechanical, and electrical.

With the gradual improvement in equipment has come a gradual growth of understanding in the art of cathode-ray instrumentation.

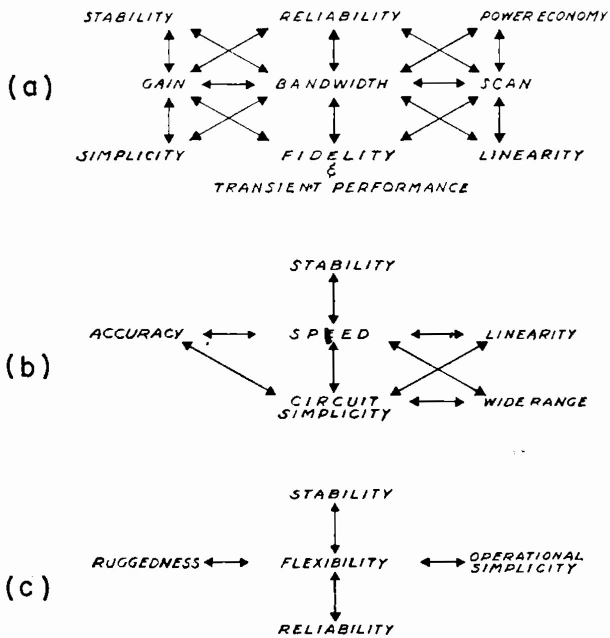


FIG. 1. Relations between various characteristics of an oscilloscope. The important point to be made is that an improvement in one factor will involve a deterioration in one or more of the others. (a) Vertical amplifier section. (b) Sweep section. (c) Operational considerations.

Various empirical principles of design have been developed, some by a flash of inspiration, some after long periods of fumbling effort. Almost always, when the concept becomes well defined, more or less clear indications of discovery and prior understanding on the part of others is revealed. This uncertainty of priority consequently makes it very difficult to assign specific credit for specific developments. Rather, the evolution of the idea in the minds of a number of individuals is the thread that can be detected.

This, then, is the point of view from which the oscilloscope and its recent developments will be discussed.

B. Background

The beginning of the cathode-ray oscilloscope can probably be dated from the first use of a cathode-ray tube as a measuring device. This seems to have occurred in 1897, in Germany by F. Braun (*1*) and in England by J. J. Thomson (*2*). The early history of the instrument has already been well documented a number of times (*3, 4, 5*). Consequently, the only review here will concern those attributes which have a direct bearing upon the latest work. The bases for most of the recent improvements in the cathode-ray oscilloscope have been in existence for some years, so that a certain amount of review is inevitable.

The oscilloscope evolved along two rather distinct lines. One was governed by the concept of *measuring events* (*4*), the other by the idea of *observing continuous phenomena* (*6*). These concepts developed in two separate branches of the electrical industry, the power branch and the communications branch. We are justified in asking just what were the major differences between the two fields that could cause such a difference in outlook?

The communications industry prior to 1940 was primarily interested in cyclical or continuous phenomena—measurements of frequency, purity of form, fidelity of amplification and attenuation, phase shift, bandwidth, modulation, etc. On the other hand, the class of phenomena of interest to the power industry (which we mistakenly tend to think of in terms of 60 cps) can be considered as single, arbitrary events—transients due to lightning strikes, insulation failure, switch action, conductor breakage, etc.

Now, to observe continuous phenomena, a recurrent sweep or timebase is desirable, and it is logical to calibrate it in terms of its recurrence rate or frequency. For single events, a timebase is required which can be initiated when needed, and the calibration must then be in terms which are meaningful for this condition, such as total sweep time, or time per unit distance on the CRT face (*7*).

Further, if the timebase is continuously running, the forward direction of the trace needs to be distinguished from the return, or flyback. As this latter portion is usually much shorter than the former, it is logical to extinguish or "blank" the trace during that time. With the initiated sweep which often spends most of the time in the quiescent state, it is equally logical to brighten or "unblank" the trace during the period of the sweep only.

Where the instrument is concerned with oscillatory phenomena, the amplifiers are normally a-c-coupled and they are often calibrated in terms of gain (i.e., $\times 1$, $\times 10$, $\times 100$, etc.) or rms volts per unit of deflection.

When transients are to be observed, the unique nature of a single event makes it desirable that the amplifiers be d-c-coupled and that the calibration be in terms of peak-to-peak volts per unit of deflection. As can be seen, two rather separate techniques and terminologies exist, depending upon the point of view. This article will be almost exclusively concerned with the instrument designed to measure single, or aperiodic, events.

Most commercial instruments prior to World War II were designed from the viewpoint of the communications industry. Of course, the requirements of radar and other pulse-handling devices demanded different characteristics, and much design work was necessary to develop test equipment adequate for the need (*8*). Even so, commercial instrumentation after the war took several years to "catch up" to the requirements of science and industry, since the only equipment available with pulse-handling capabilities were those which had been designed specifically for the development and maintenance of radar and television.

On the other hand, the power industry for some time had been designing equipment to respond to single events as outlined above.[1] Many of the concepts incorporated in this equipment anticipated those embodied in the best present-day oscilloscopes. It appears, however, that little reference was made by the designers of the conventional instruments to the available published material concerning this prior equipment (e.g. Kuehni and Ramo, *4*). Thus, the realization came slowly that an instrument designed to display a completely arbitrary sequence of events could easily display the special case of a uniform succession of uniform events. After all, sine waves, square waves, and other phenomena of a cyclical or continuous nature can be considered but an endless succession of similar single events.

Essentially, a CRT display is a graph of two or possibly three variables. Usually, an arbitrary or unknown variable is plotted against one or two known variables; i.e., a television display plots light intensity against distance on arbitrary X and Y axes; a radar plan-position indicator plots the presence or absence of reflections from objects against distance and direction axes; etc.

An oscilloscope normally plots an arbitrary electrical voltage against time. In other words, an oscilloscope is simply a sophisticated, graph-

[1] As early as 1927, Dr. Gabor (*9*) of Germany described an instrument which was functionally very similar to the better present-day oscilloscopes. A transient signal from the power mains initiated the multivibrator-controlled sweep generator and unblanked the cathode-ray tube; in the meantime, the attenuated signal was passed through a delay cable, and appeared on the vertical plates of the cathode-ray tube after the sweep was well started. The attenuators were frequency-compensated to maintain signal fidelity, and the multivibrator which controlled the sweep generator was of the bistable type to prevent more than one sweep occurring.

drawing device with internal circuitry designed to give a linear, undistorted voltage change bearing some known relationship to time and to whatever the unknown phenomena is.

The electrical analog of the unknown phenomena is called a "signal" and is the entity on which the oscilloscope operates. The tremendous range of signals handled by the oscilloscope is typified by the few microvolts of fluctuation of a stimulated brain cell and the several-hundred-kilovolt surge of a high-tension impulse generator; by the fraction of a microsecond appearance of a subatomic particle and the changing level

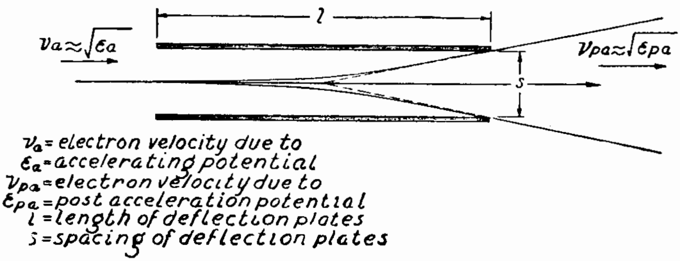


FIG. 2. Pertinent factors affecting the performance of a pair of deflection plates.

of a d-c voltage. Much of the recent development in the cathode-ray oscilloscope stems from efforts to encompass these needs, as well as to stabilize the performance and improve the reliability of operation.

II. Cathode-Ray-Tube Development[2]

A. Standard Tube Types

For some time the CRT has had a limiting effect on oscilloscope development in several respects. A superficial review of the important factors affecting tube performance will help to clarify this situation.

To the instrument designer, three of these factors are possibly more interesting than any others. These three are bandwidth (of the deflection system itself), sensitivity (or deflection factor, in terms of the number of volts needed to deflect the beam a given distance), and scan (the size of the display on the tube face). These three are interrelated in a somewhat mutually exclusive fashion, and therein lies the problem for the instrument designer.

Referring to Fig. 2, it can be seen that there are four parameters that can have a primary effect upon the performance of the CRT:[3] the

[2] For a fuller discussion of CRT design, production, and performance, see Moss (*10*).

[3] Excellent discussions of deflection systems can be found in several texts, notably those of Millman and Seeley (*11*), Harman (*12*), and Hutter (*13*).

acceleration potential, the post-acceleration potential, the length of the plates, and their spacing.

In the final analysis, the effect of a deflection system on an electron will be determined by the configuration of the system, the intensity of the deflecting field, and the time which the electron spends in the deflecting field. We shall assume the classical parallel-plate deflection system for the purposes of this analysis, although we shall examine some modifications of this later in the article.

The time during which the electron is in the deflecting field is determined by its initial velocity and length of the deflecting plates. The intensity of the deflecting field is determined solely by the spacing of the plates (assuming a constant deflection potential). Using these factors, we can deduce their effects on the three performance parameters which are of interest to the circuit designer.

The bandwidth of a deflecting system is determined by the "transit time" required for an electron to pass between the plates. When the impressed frequency is such that the period of one cycle approaches within an order of the transit time, deterioration and distortion of response will begin to be noticeable. The "3-db" point of response[4] is at a transit time that represents slightly less than one-half of a cycle. It is evident that the bandwidth is inversely proportional to the length of the plates and directly proportional to the velocity of the electron (which is proportional to the square root of the accelerating potential).

However, the sensitivity of the deflection system is directly proportional to the time that the electron is between the plates. Consequently, we find that lengthening the plates (or decreasing the accelerating potential) will increase the sensitivity, but at the expense of bandwidth. Sensitivity also can be increased by reducing the spacing of the plates, and here there is no corresponding decrease in bandwidth.

Scan, on the other hand, is dependent only upon deflection plate length and spacing. Increasing the scan by increasing the spacing decreases the sensitivity. Increasing the scan by shortening the deflection plates increases bandwidth but decreases sensitivity. It is obvious that a process of judicious selection must be used to obtain the most useful combination of characteristics for a particular use.

The post-acceleration potential acts as a converging lens in accordance with well-known physical principles (*14*, *15*). The degree of convergence is determined by the configuration of the post-acceleration anodes, but *always* works to reduce both the scan and sensitivity, as the degree of post-acceleration is increased.

One of the problems facing the oscilloscope designer is then simply

[4] See Appendix.

this: if he uses a conventional CRT with a high deflection sensitivity, he is confronted with a bandwidth limitation which is approached by the best amplifier capabilities; if the response of the CRT extends into the ultrahigh-frequency region, the sensitivity of the tube is so low that an inordinately high amplifier gain is required, with its attendant low bandwidth. Consequently, a broad area of low-level, short-risetime signals

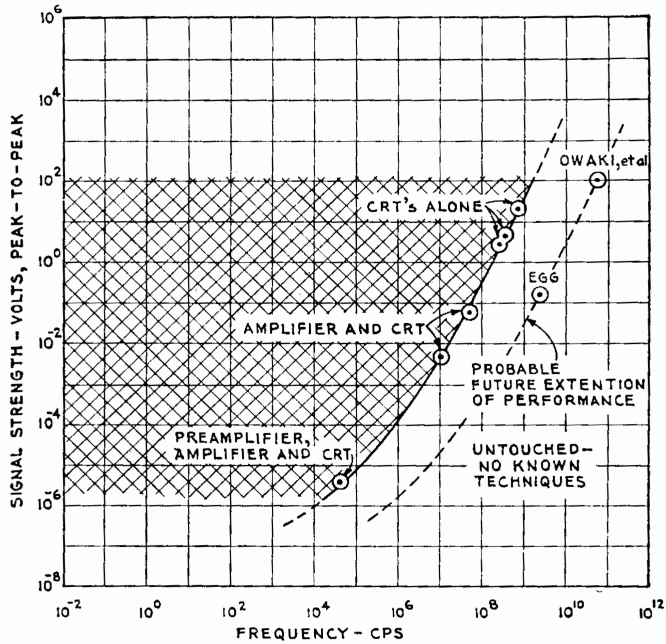


FIG. 3. Approximate area of performance of cathode-ray tubes and various accessory equipment. The limits are only approximate and should not be taken too literally. Nevertheless, they serve to indicate the present capabilities, the probable future performance and the untouched "problem" area.

can be handled neither by an amplifier-CRT combination nor by a CRT alone (see Fig. 3).

As the demands for more usable bandwidth become greater, another decision faces the instrument designer. Increased bandwidth in the amplifier can be obtained at the expense of gain, output voltage swing, or both. This, in turn, requires a higher sensitivity on the CRT which can only be obtained at the expense of scan, since we are aiming primarily for greater bandwidth. However, nearly all deflection plate designs a few years ago permitted the beam to scan beyond the edge of the fluorescent screen, and anything less seemed to be a step backward to the designer.

When it is considered that the extra current required in the deflection amplifiers for a large voltage swing, with the resultant increase in power-supply requirements, is expensive in terms of components, reliability, and power consumption, as well as instrument cost,[5] it becomes apparent that decreased scan is preferable to lower sensitivity, lower bandwidth, or both.

Providing an additional influence on such a change was the increasing usage of photography for recording oscilloscope traces, especially for higher frequencies and single events. Of course, photographic enlargement can compensate somewhat for decreased display area, but it also requires a higher intensity of trace where single sweeps are of interest, and since this can only be gained by the use of greater beam currents (which means a larger spot size) (*16*) or higher accelerating potentials (*17*) (which means a lower deflection sensitivity), it can be seen that a restriction in display area was again the logical step.

Consequently, several new tubes have appeared in succession, each representing an advance over the previous ones. Accelerating potentials have been increased to 10, 20, and 30 kv, giving brilliant traces at high speeds for single-sweep photography. Spot diameters have been decreased significantly and deflection sensitivity increased. These improvements are the results of several changes in design.

1. Intensification. Intensification was first accomplished by increasing the voltage between cathode and deflection system. However, each such increase in intensity causes a corresponding decrease in deflection sensitivity. One of the first steps to alleviate this situation was to produce a large portion of the electron acceleration *after* the beam was deflected. (This is called "post-deflection acceleration" or PDA.) This is done by placing a high voltage on the interior dag coating of the bulk of the CRT. (see Fig. 4). It was found, however, that beyond a certain PDA voltage, the sensitivity of the deflectors are decreasingly effective, owing to the focusing effect of the accelerating field (*15*). The next step, therefore, was to break the dag coating into several rings with ascending voltages as the beam progressed toward the screen (Fig. 4b). This changed the

[5] As an illustration, consider the problem of designing a dc-30 MC amplifier to give a 10-cm deflection on a CRT with a deflection factor of 25 volts/cm and a total stray input capacitance of 20 $\mu\mu$f. The total voltage swing required is 250 volts. Without going through all of the computations, it is found that the best available 100-watt tetrodes are necessary, that the total dissipation in the load resistors is approximately 450 watts, and that the maximum gain obtainable from the stage is 3! This requires a somewhat similar stage to drive it, thus reducing the total system bandwidth which can be recovered only by reducing the load resistance, thereby reducing the gain, which required more stages and reduces the bandwidth further. Obviously, some other means must be found to solve the basic problem.

focusing effect from that of a single strong lens to that of several weak lenses.

The most recent step in this direction was one which had been invented in Germany in 1938, by E. Schwartz (*18, 19*), but had been ignored as impractical until C. H. Vollum independently suggested it in 1952–1953 (unpublished). This consisted of winding a resistive ink in a helical form on the inside of the glass bulb and placing the post-deflection voltage

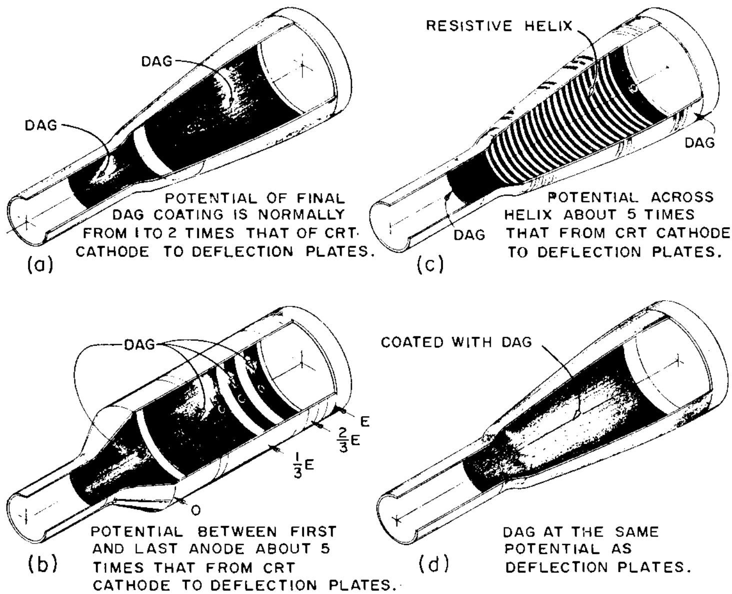


FIG. 4. Various arrangements of postdeflection acceleration anodes. The tendency has been to decrease the potential difference between any two adjoining anodes, while maintaining the same total acceleration potential (a) Simple post-accelerator CRT. (b) Multiple-band post-accelerator CRT. (c) Helical post-accelerator CRT. (d) Mono-accelerator CRT.

across it (see Fig. 4c). The resultant effect on the electron beam is that of a relatively low, uniform electric field (≈ 350 volts/cm) directed along the axis toward the screen. With one exception, this design provides possibly the most distortion-free characteristics of any known design, and a number of tube manufacturers have adopted it as a production technique.[6]

The one exception to the foregoing statement is what is known as the "mono-accelerator" tube (*20*) (Fig. 4d). This design has all the accelera-

[6] Twentieth Century Electronics, Ltd., EMI, Ltd., Ferranti, Ltd., GEC, Ltd., all of England; Allen B. DuMont Laboratories, Edgerton, Germeshausen and Greer, Electron Tube Corporation, and Tektronix, Inc., all of the United States.

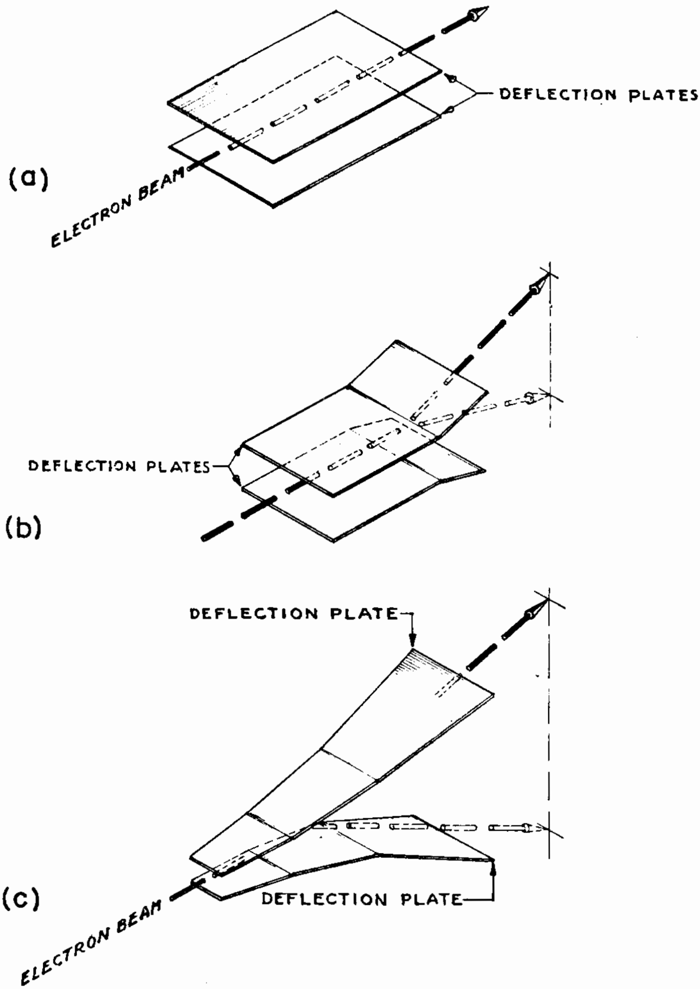


FIG. 5. The development of simple deflection-plate structures. The "flaring" evident in (c) is to insure that the force vectors will be parallel in the region of beam travel, rather than distorted as they are near the edge of the plates. (a) Classical deflection plates. (b) Single-bend deflection plates. (c) Multiple-bend, shaped deflection plates.

tion take place in the electron gun, and the drift space between the deflection plates and the screen is field-free. Consequently, any distortion is due to the design of the deflection system only. The display of such a tube is quite remarkable for its linearity and focus, and the current is significantly increased because of the higher focusing fields between the various

TABLE I. Cathode-Ray Tubes

Tube type	Operating volts: Acceleration	Operating volts: Post-acceleration	Vertical deflection factor, v/cm	Vertical scan, cm	Volts for total scan	Useful bandwidth, Mc
Low-writing-rate types						
5CP-A EIA[a]	1500	3000	23	12.5 full screen	290	. . .
5ABP EIA	1500	3000	12.4	10	124	. . .
5AQP EIA	2500	. . .	14	10	140	. . .
T52P Tektronix	1650	4000	10	10 minimum	100	. . .
T56P Tektronix	1050	4000	11	8 minimum	88	. . .
5AMP EIA	2500	. . .	9	6.3	57	. . .
3WP EIA	1500	. . .	18.5	5.8	107	. . .
T31P Tektronix	1850	. . .	12.6	5.1	64	. . .
High-writing-rate types						
5RP-A EIA	2000	8000	45	4	192	. . .
5XP-A EIA	2000	12000	18	4	72	≈200
5BG-P EIA	1670	10000	12.5	6	75	≈185
5BH-P EIA	1670	10000	6.5	4	26	≈125
5ATP EIA	6000	. . .	15	4	60	≈2000
KR3[b] EGG	1400	11400	2.9	4	12	≈2000

[a] Formerly RETMA.

[b] Actual display area of EGG tube is *0.4 × 0.6 in.*, and deflection factor is given as deflection "sensibility," or volts per spot diameter. However, the listed figures have been *adjusted* to permit a comparison with the regular types of CRT. Note the vast improvement in bandwidth capability.

electrodes. This higher current density makes it possible to obtain a higher photographic writing rate for the same over-all accelerating potential than is possible in the PDA type of tube.

However, if the accelerating potential of the mono-accelerator tube is changed until the photographic writing rate equals that of the PDA tube, the deflection sensitivity is significantly smaller, requiring compromises in bandwidth for its improvement.

2. Deflection-Plate Design. Other design changes which have improved the performance of CRTs concern the deflection plates themselves. The classical deflection system is a pair of parallel plates, of the proper spacing and length to give the desired combination of sensitivity and display area (Fig. 5a). The first improvement moved the plates closer together to improve the sensitivity and bent them apart at what would be the interception point to increase the scan (Fig. 5b). However, it is apparent that the deflection sensitivity is not uniform over the whole area of deflection; e.g., one volt does not give as much deflection in one portion of the screen as in another, often because the electron beam traverses the deflection field at a different angle in some regions from others. Since only the normal component of the field affects the beam, the sensitivity will naturally vary according to the region of travel.

A solution to this was to calculate a plate shape that produced a deflection field such that the deflected beam was everywhere normal to the field, and then to approximate this shape by a series of straight segments which avoids the practical difficulty of reliably forming the metal into such a shallow curve (Fig. 5c). The plates have also been lengthened to increase the time during which the beam is subjected to the deflecting field and flared in width to decrease the interplate capacitance as much as possible and yet keep the "edge" effect limited to areas where it will least affect the beam.

While these last two measures improve the sensitivity and reduce distortion, they have also increased the interplate capacitance and the transit time, both of which determine the upper limit of the frequency response. Consequently, these changes have resulted in a decrease in high-frequency capabilities. Fortunately, the high frequency limit still lies beyond the capabilities of most amplifiers and so does not seriously impair the overall performance of the system (see Table I).

B. Ultrahigh-Frequency (UHF) Tube Types

However, even the above changes have resulted in "figure-of-merit" improvement of not more than fivefold. Presently, available tubes of the standard type have a high-frequency response limit of 125 Mc and a deflection factor of 6.5 volts/cm at the normal operating potentials, with some prospect of a slight increase. To vault into the ultrahigh-frequency region at low signal levels requires techniques of a completely different order.

This problem has been investigated and attacked over a period of many years. Hollman (*21*, *22*, *23*), for instance, has been one of the most prolific writers on the subject, first in Germany and more recently in the United States and a number of fruitful suggestions have been made. Von Ardenne (*24*, *25*) and Lee (*26*) have each contributed partial solutions to the problem, with deflection systems designed around very minute or "micro" electron beams. However, it remained for J. R. Pierce (*27*) to point out a practical solution with his distributed-plate deflection system.

Basically, the problem is one of subjecting an electron beam to either a more intense deflecting field than normal or for a relatively longer period of time to a weak deflecting field. Partial solutions to each were discussed in the preceding paragraphs, i.e., decreasing the spacing between plates, increasing their length, or both. Stated in the form of a question (which implies the solution), can the same electron be subjected to the same deflecting field (no matter how transient) for as long as necessary to obtain the desired deflection? The problem has a number of counterparts in many other fields. The cyclotron, the magnetron, and the klystron are all early examples of solutions in a particular form.

Pierce's suggestion recognized that the electron has an initial velocity normal to the deflecting field and consequently occupies a different point in space at each successive instant of time. If, then, the deflecting field could be controlled to propagate at the same velocity as the electron beam, even a relatively small and short-duration signal could exert a measurable influence on each individual electron. Pierce designed a deflection system which is in essence a delay network, with the lumped capacitance formed by a series of deflection plates, each separated by small inductances (see Fig. 6a). The electrons are projected into the system with a velocity of the delay network. The form in which Pierce presented the system was somewhat cumbersome to use (it required a microscope to view the trace), but it was definitely a major contribution to the design of CRTs.[7]

Not quite a year later, Owaki *et al.* (*29*) described a deflection system developed in Japan during World War II. The deflectors consist of parallel wires folded in a zigzag manner normal to the direction of the electron beam (Fig. 6b). Although the sensitivity is substantially less

[7] It is interesting to note that Dr. A. V. Haeff (*28*) submitted a patent application on a deflection system of this type in 1933. While his main idea was for it to be used in a high-frequency detector, it certainly incorporates the traveling-wave concept.

than that provided by Pierce's design (owing to the system configuration), it remains essentially constant up to about 15,000 Mc.

A further advancement in this direction was made by Smith *et al.* (*30*). Their deflectors are constructed of metal ribbon, flat-wound in a helical fashion to a "D" shape, and placed inside a similarly shaped ground

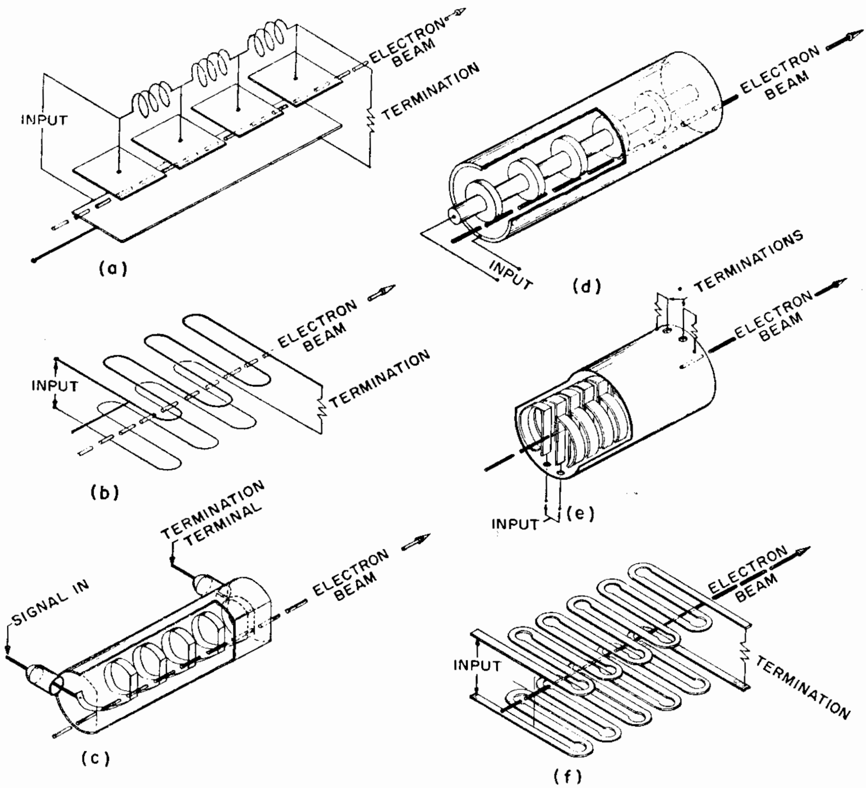


FIG. 6. The development of the distributed plate deflection system. (These drawings are highly schematic and should not be taken as literal representations of the various systems.) (a) Pierce (*27*). (b) Owaki *et al.* (*29*). (c) Smith *et al.* (*30*). (d) Lee (*31*). (e) Germeshausen *et al.* (*32*). (f) Moulton (unpublished).

plane (Fig. 6c). The electron beam passes between the flat portions of the D's. The system was designed with an impedance of 50 ohms, and was meant to be "inserted" in a 50-ohm coaxial line to enable signals to pass through and be viewed in passing without being distorted.

Lee (*31*) modified his micro-oscillograph to include traveling-wave deflectors, obtaining useful performance to 10,000 Mc and beyond. His deflectors are of the coaxial type, with disks machined on the central conductor at intervals (Fig. 6d). The electron beam is then directed longitudinally down the space between the disks and the outer cylinder of the coaxial line.

Germeshausen *et al.* (*32*) have recently designed a tube which brings to commercial instrumentation the advantages of this type of deflection system.[8] Their tube makes use of two D-shaped deflectors of the Smith, *et al.*, type, inserted in a cylindrical shield (see Fig. 6e). The performance which they have obtained represents a remarkable advancement in the CRO field (see Table I).

An additional design for this type of deflection system has been made by C. H. Moulton (unpublished). A pair of flat sheets, electro-etched to form a closely spaced zigzag conductor, forms the distributed deflection system (Fig. 6f).

III. Amplification Techniques

The deflection amplifier has presented an even more immediate and severe limitation on frequency response than has the CRT. The peculiar requirements which an oscilloscope amplifier must meet (maintenance of signal fidelity, wide frequency response including direct current, etc.) have generally ruled out the use of the techniques developed to increase gain and bandwidth for single-frequency amplifiers. Most oscilloscope users apparently want the amplifier response of their instrument to extend from direct current to the highest frequency possible, and this is not always consistent with the sensitivity they must have for their particular purpose. Consequently, new designs have been necessary for any significant improvements in gain-bandwidth product.

A partial solution to the gain-bandwidth problem has been available for some years, since W. C. Percival (*33*) of Great Britain patented his unique amplifier design in 1937. Theoretically, it enables a gain-bandwidth product almost as large as desired to be obtained. Variously called the "chain amplifier," "transmission-line amplifier," and "distributed amplifier," it consists of a series of identical tubes arranged with their plates and grids distributed at intervals along a pair of lumped-constant simulated transmission lines (see Fig. 7). The grid-cathode and plate-cathode capacitances form an essential part of the lumped capacitance of the network. The "secret" of the performance is that the input and output capacitance of the individual tubes are electrically separated by the inductances, and consequently a signal generator "sees" only the input capacitance of one tube. However, the amplitude of the output signal is equal to the sum of the amplitudes of the signals from each

[8] For an excellent, concise, and readable analysis of the factors relating to the design of such a tube, their article is highly recommended.

individual section. In other words, the total gain is equal to the section gain (that of one tube) multiplied by the number of sections used. As can be seen, even a section gain of less than one becomes useful.

The distributed amplifier circuit was little noticed until 1948 when Gintzon *et al.* (*34*) wrote the definitive paper on the subject. In 1949, Rudenberg and Kennedy (*35*) described a 200-Mc amplifier which they had designed using this technique, and the same year N. B. Schrock (*36*) described a 150-Mc unit. In 1950, Horton *et al.* (*37*) published a follow-up article on Gintzon *et al.* At about this time, Belleville (*38*) completed an amplifier for a high-speed oscilloscope, using the same technique. Although none of these circuits is d-c-coupled, Yu *et al.* (*39*) described a design with this feature, shortly after several commercial oscilloscopes

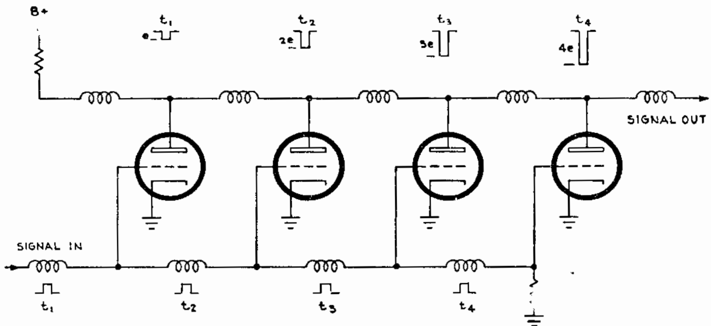


FIG. 7. Simplified distributed amplifier circuit. In practice, there are small trimmer capacitors between the grids and ground, and the plates and ground. These parallel the interelectrode capacitances and make it possible to match the propagation velocities of the grid and plate circuits.

(*40*) appeared, incorporating d-c response. However, the distributed amplifier technique is not yet widely used in the oscilloscope field, perhaps because of its relative expense and design complexity.

IV. Sweep Circuits

While the recent improvements in deflection amplifiers and CRTs have been substantial, perhaps the improvement in the operation of the timebase circuits has been the most spectacular of all in the last few years. Almost all this advance has come as the result of changes in the conception of timebase operation, rather than from radical new circuits. In fact, most of the circuit elements presently being used in the most advanced CROs have been in existence for many years, but the total configuration is the recent development which is responsible for the improved performance.

An examination of some of the influences responsible for the change will help to show why the new timebases have assumed the configuration they presently have. Obviously, it would be quite impossible to detail all the background to even one development, much less a whole class of developments; nevertheless, certain general points can be examined.

A. Some Helpful Definitions

Before the discussion of the timebase circuits is undertaken, several terms which are of significance should be explained.

1. Triggering. The first of these is the concept of "triggering." Generally, a triggered action is one which is not self-sustained after it has been started by an initiating signal (see Fig. 8a).

Examples would be the firing of a gun (under single-shot conditions), the flashing of a flashbulb, energizing of a simple resonant circuit by a single impulse, etc. A trigger signal is then one which initiates a single cycle of operation, no matter how complex, of some device.

2. Gating. Another concept is that of "gating." A gated operation is one which is self-sustaining or externally sustained once it has been initiated and must be terminated by the removal or termination of the gating signal. Examples are the firing of a machine gun, the oscillation of a resonant circuit with regenerative feedback, the flow of water through a water faucet, etc. A gating signal is then one which permits a device to operate for the duration of the signal (Fig. 8b).

3. Synchronizing. The term "synchronizing" actually has two meanings, one essentially descriptive and adjectival, describing a condition, the other essentially operational or verbal, describing a process. Thus, two operations are said to be "synchronized" when their separate elements occur in a one-to-one relationship to each other, even though there may be no direct connection or control between them. On the other hand, when one operation exerts some kind of control over another (continuous and self-sustaining) operation so that there is a one-to-one or other integral relationship between them, it is also said that they are "synchronized." In this second case the control is usually exerted by forcing a particular portion of the latter operation to occur before it normally would (Fig. 8c).

4. Arming. The operation of "arming" is somewhat more subtle than the others, in that some subsequent operation does not *necessarily* follow it. It only makes a subsequent operation possible. Examples are the setting of a mousetrap, the action of a timeclock on a safe (the safe cannot be unlocked until the time clock has gone off; afterwards it does not have to be opened, although it can be) the energizing of an electronic circuit so that it can work if called upon, etc. (see Fig. 8d).

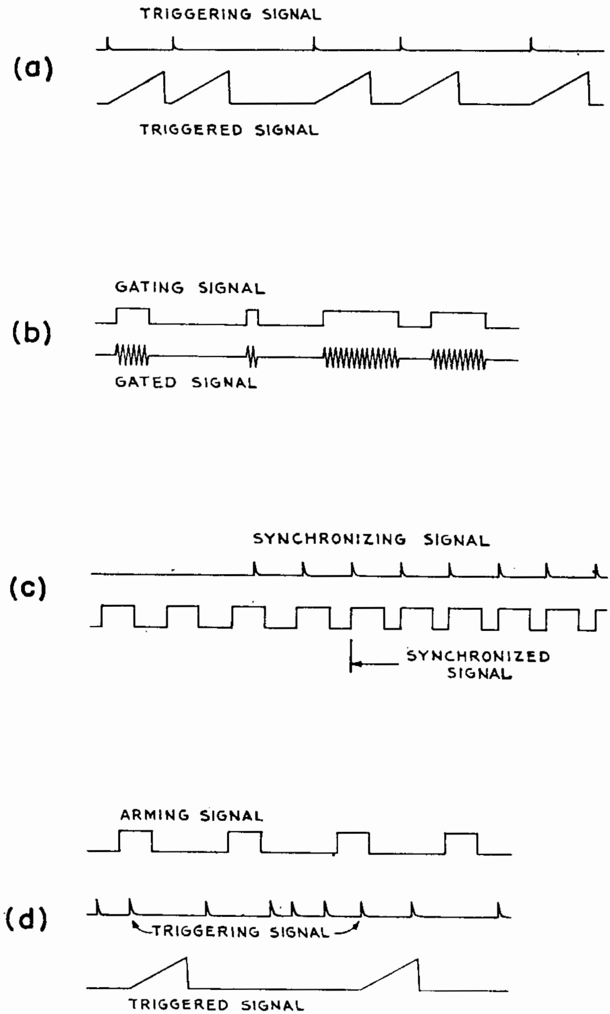


FIG. 8. Examples of various circuit functions. (a) Triggering. (b) Gating. (c) Synchronizing. (d) Arming (with triggering). Notice in (c) that the dependent signal does not become synchronized until a particular section of it can be forced to occur prior to its regular occurrence. In (d) the triggered signal can occur only if a triggering signal occurs during the "armed" period.

In all these examples, it is assumed that none of the other necessary conditions for operation change; e.g., the ammunition does not run out, the battery does run down, the reservoir does not run dry, etc. If this is assumed, these concepts permit some sophisticated and highly useful operations to be performed.

B. Timebase Initiation

As implied earlier, one of the principal requirements for any type of timebase is that it can be started or triggered at the proper time with relation to the phenomena it is to display (see Chapter 4 in Puckle, *7*). If subsequent cycles of operation are required, the same time relationship should be maintained unless deliberately changed.

An analysis of signals to be viewed reveals that the common denominator of them all is voltage or current change. If some method of detecting a given voltage level is available, the initiation of the sweep generator can be made stable with reference to at least one signal parameter.

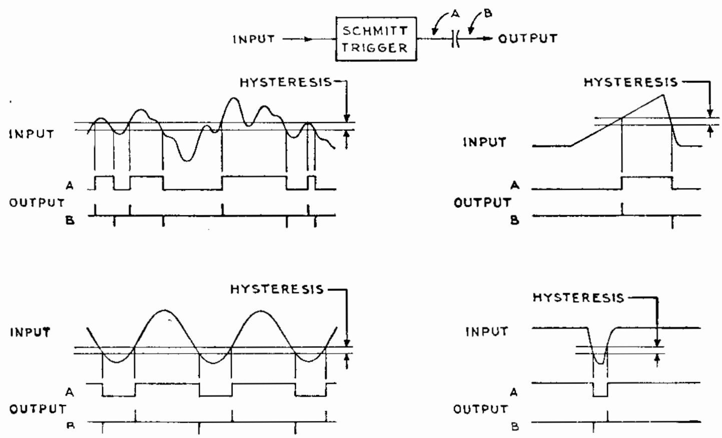


FIG. 9. Performance of the Schmitt trigger circuit when responding to various input signals. The transition time in a well-designed circuit can be considerably less than 0.01 μsec.

Several methods of voltage-level discrimination exist (see Chapter 5 in Puckle, *7*). Possibly one of the most useful is the one developed by Schmitt in 1938 (see *41*, *42*, and p. 81 in Puckle, *7*). Essentially, it is a bistable device, whose state depends upon the level of the input voltage. The change of state of the output takes place because of the regenerative action of the circuit, at a given d-c level at the input. In terms of the performance, the output plate goes through a very rapid positive voltage transition from one d-c level to another whenever the input signal passes through a certain d-c level with a *rising* (positive) slope, and an equally rapid negative transition to the original state when the input passes through a slightly lower d-c level with a *falling* (negative) slope (see p. 81 in ref. *7*). The transitions are the same whatever the character of the input signal, and consequently the output consists of numerous very rapid transitions between two voltage levels separated by only a few volts. The occurrence of the transitions depends completely upon the character of the input signal (see Fig. 9). In practice, a few-$\mu\mu$f capacitor differentiates the transition into a fast pulse, which is injected into the multivibrator. This type of performance gives the circuit not only voltage level recognition but also slope recognition, e.g., rising or falling—and signal shaping as well. To the oscilloscope designer this is a most valuable attribute. It permits him to design sweep-generator controlling circuits that must respond to only one type of signal, considerably simplifying his task. To permit the instrument to respond to signals of the opposite polarity, a phase-inverting amplifier is inserted ahead of the Schmitt circuit (most instruments incorporate such a circuit.)

C. Timebase Generation

Another feature of great importance to the user of a CRO is that the sweep generator develop a "linear" sawtooth.[9] Although many types of

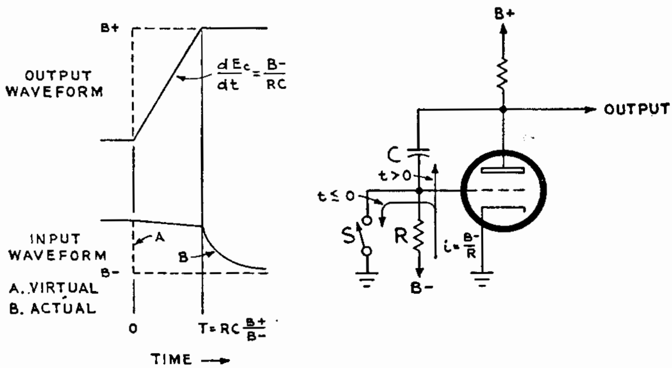


FIG. 10. A basic Miller sweep generator and associated waveforms. This performance is simplified for the purposes of explanation.

sweep circuits exist (see Chapter 3 in Puckle, *7*), only a few develop a "linear" voltage change directly. Most depend on taking a small segment of an exponential voltage change and amplifying it.

Much of the recent improvement in sweep generation has been the result of circuits employing the Miller (*43*) effect circuit. Miller first described this effect before 1919, but little was done with it until World War II. Figure 10 illustrates a basic Miller-effect circuit, with "run-up"

[9] Certain types of displays or measurements require special, nonlinear sweep waveforms. However, we will only deal with the linear type in this respect unless otherwise specified.

operations. Although the operation is simple, it is elegant and highly useful.

If we neglect the capacitor (C), it will be seen that the circuit is a simple d-c amplifier. Consequently, any signal impressed on the grid of the tube appears on the plate in an amplified and inverted form. In practice, the gain of this amplifier is largely responsible for the quality of linearity of the sawtooth waveform. For this reason, pentode tubes, with their inherently higher gain, will be found in most of the sweep generators which use the Miller effect.

Let us assume that the switch (S) is initially closed. The grid and cathode are then at the same potential, so that the tube is conducting heavily. Consequently, the plate potential is just positive enough with respect to the cathode to keep the current flowing—perhaps +2 or +3 volts, depending upon the tube characteristics.

Assume that the switch is opened at time $t = 0$. Immediately before the switch opens, a current, defined by the voltage drop across the resistor divided by the resistance of the resistor, is flowing through the resistor and through the switch to ground. When the switch is opened, the current cannot stop immediately. In fact, if it were to vary at all, the voltage on the grid would change, which in turn changes the voltage on the plate. As the diagram shows, the capacitor (C) serves only to impress any plate-voltage change directly on the grid. It will be appreciated that since this is an amplified, inverted version of the signal appearing on the grid, this action powerfully stabilizes the potential of the grid.

As the result of this feedback, the potential drop across the resistor (R) remains essentially constant. Consequently, the current flowing into the grid side of the capacitor (C) also remains constant, and thus the voltage on the plate side of the capacitor rises or "runs up" at a linear rate, determined by the amount of current and the size of the capacitor. At a time $T = R_gC(B+/B-)$,[10] the plate will reach $B+$ potential, the tube will be cut off and will remain in this condition until the grid is clamped by closing the switch.

In reality, the grid voltage does decrease a very slight amount as

[10] In operation the output waveform can only run from approximately 0 volts to $B+$. The drop across the grid resistor R_g determines the capacitor-charging current, and since the grid voltage is essentially fixed at zero volts, the potential difference is equal to the $B-$ voltage. The voltage across C will change in accordance with $dE_c/dt = i/C$; but $i = B-/R$, so $dE_c/dt = B-/RC$, or $T = \int_0^{B+} (RC/B-)dE_c$. Consequently, $T = RC(B+/B-)$ to an accurate first approximation. In other words, the tube characteristics do not enter into the determination of the circuit performance to any significant degree.

required to decrease the tube current, but the departure from the conditions described here will be only a small fraction of 1% in a well-designed pentode circuit.

Another way of looking at the Miller sweep generator is by considering the *RC* portion of the circuit as a current-carrying device. The grid of the amplifier tube monitors the current (by measuring the voltage across the resistor *R*) and adjusts the voltage at the top of the capacitor to keep the current flow into the capacitor constant.

The circuit is easily modified for the "run-down" performance and to adapt it to peculiar circuit conditions. The British developed a number of Miller-effect circuits during World War II, with such exotic names as phantastron, sanatron, sanaphant (*44*), etc. However, they were generally overlooked in the United States until after the war.[11] Even then they were adopted rather slowly. The first of record for oscilloscope use was a relatively slow-speed, screen-coupled, phantastron type developed by C. H. Vollum (unpublished[12]) in 1948–1949. Despite its high-speed limitations compared with a multivibrator-controlled *RC* type (a not very linear 30-μsec sawtooth was the shortest it would develop), the linearity, stability, and reliability over most of the sweep range were much beyond anything then used.

The bootstrap circuit was used only to a limited degree as a CRO sweep generator, and then mainly because of its high-speed capabilities. Vollum and Rhiger (*45*), for instance, used it in a high-speed oscilloscope developed in 1948–1950. However, most commercially available instruments used the well-known thyratron-controlled *RC* circuit, while a few higher-priced instruments used the multivibrator-controlled *RC* circuit. The bootstrap circuit has been revived in recent years as a wide-range sweep generator and magnifier circuit in one of the better high-performance instruments (*46*).

D. Timebase Duration

Another problem with the sweep generator concerned the *duration* of the sweep (the length, as seen on the screen). The thyratron type of sweep generator depended upon the firing and extinguishing voltages of the gas tube to determine the start and end of the waveform. The multi-

[11] Actually, in this country, development of sawtooth generators took place mainly in terms of the bootstrap circuit, and it was not until after the war that the Miller action was identified. It was recognized that the Miller integrator and the bootstrap were two of several possible modifications of a basic circuit, differing only in the choice of ground point, signal injection point, and the power-supply location. Each has advantages and disadvantages with respect to the other, and Professor F. C. Williams (see Sect. 2–6 in ref. *44*) has given an excellent description of the comparative performance.

[12] Circuit was used in the Tektronix Type 512 Oscilloscope.

vibrator-controlled type (see Sect. 5.5 in ref. *44*) (both *RC* and bootstrap circuits) depended for duration control upon the length of the unstable portion of the multivibrator cycle. Neither of these provide a duration that is particularly stable.

In a sense these circuits can be called "straight-through" or "sequential" circuits, since each circuit element is controlled by the one before it and controls the one that comes after it (see Figs. 15a, b, c, and d).

The situation can be solved in terms of d-c levels. If we assume that our sawtooth generator is linear and stable in performance, then a given voltage change can be used to measure a desired lapse of time. Consequently, a circuit to detect a given d-c level can be used to initiate the

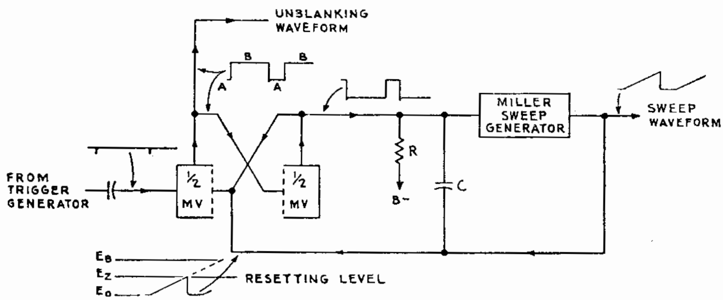


FIG. 11. A sweep duration-controlling circuit. The d-c levels are adjusted so that the resetting point of the multivibrator represents a voltage excursion of the sweep waveform which is just sufficient to deflect the beam the desired space on the CRT. In practice, various cathode-follower circuits are used to obtain isolation, coupling, function introduction, etc. (See section in Appendix on cathode followers.)

resetting of the controlling multivibrator (*47*). A resetting circuit of this type insures that the length of the sweep, as seen on the CRT screen, will remain constant, which is a desirable feature for the user. Notice that this type of circuit implies the existence of a feedback loop—multivibrator triggers sweep generator, which in turn resets multivibrator (see Fig. 11). (Naturally, there will be various isolation circuits included which are not shown in this highly simplified schematic.)

E. Timebase Isolation

An additional shortcoming of the "straight-through" type of sweep circuit reveals itself most dramatically during certain types of operation. As an example, an oscilloscope can be used to display the output of a scintillation counter (*48*, *49*). With the aid of auxiliary equipment, a rapid means of measuring the gamma-ray energy spectrum and consequently identifying the materials, is available. It was found, however, that the known low-energy portion of the spectrum was missing. Analysis of the situation revealed that the problem resided in the conditions that existed during the resetting of the sweep generator and multivibrator, before quiescent conditions had been reached. As the circuits are returning to normal, a short period exists when the sensitivity (of the multivibrator) to a trigger pulse is increasing. If a high-energy pulse occurs during the early portion of this period, it will trigger the circuit, whereas a low-energy signal will have no effect. It can be seen that no matter what the distribution of energy is, the high-energy pulses will be favored to a greater degree than their statistical occurrence justifies.

This situation can be partially solved by using a Schmitt trigger circuit to initiate the operation of the multivibrator, as it generates a

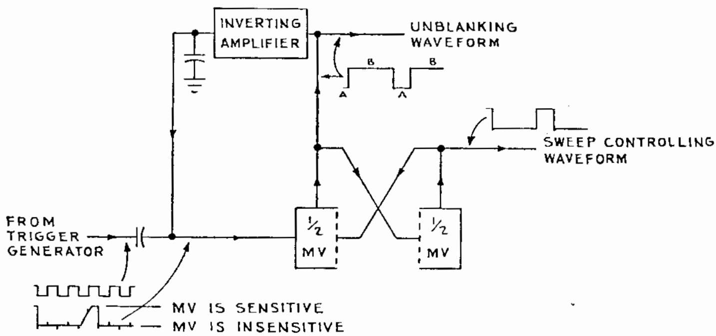


FIG. 12. An input-protection circuit to prevent interference with the sweep-generation cycle until all circuits have reached a quiescent state. (Most instruments now combine this circuit with the one in Fig. 11.) This feature makes the instrument as responsive to a low-energy signal as to a high-energy one.

standard trigger pulse. However, even this will not completely solve the problem, since a trigger can still occur during the resetting period of the multivibrator and cause a slight amount of time instability or jitter.

A better solution would be to isolate the input to the multivibrator from the start of the cycle until the circuit has completely "relaxed" at the end of the cycle. In this way, identical conditions of operation are established for each cycle of sweep operation, and one more factor leading to instability is removed. Isolation can be accomplished in a number of ways. The use of diodes, cathode followers, etc., in conjunction with negative or positive gating signals offers a multitude of methods of the design engineer (*50*). Note again that the idea of a feedback loop is implicit here: trigger output initiates multivibrator; multivibrator blocks own input and holds off reactivation until all circuits have "relaxed" (see Fig. 12). (Again as in the previous circuit, Fig. 11, there are appropriate isolation stages at pertinent points of the circuit.)

F. Minimizing Duty-Cycle Effects

A further problem has been solved by d-c-coupling the sawtooth waveform from the sweep generator through the amplifiers to the CRT (*51*). In an a-c-coupled circuit, changes in duty cycle of the sweep waveform cause several problems, such as change in sweep timing, change in sweep starting level, etc. Direct-current restoring by means of diode clamping in later stages can correct some of these problems, but it is not wholly satisfactory. On the other hand, d-c-coupling requires a greater range of power-supply voltages to permit the various circuits to operate at the proper d-c levels, which adds to the cost of the equipment.

G. Unblanking Methods

Control of intensity is also affected by a changing duty cycle. Because the deflection plates usually operate in the vicinity of ground potential (to simplify the design of the deflection amplifiers), the cathode and grid of the CRT are normally required to operate at 1 to 4 kv negative, or as much as 6 kv for a monoaccelerator CRT. Consequently, connection of the unblanking waveform to the CRT grid is generally made through a capacitor (see Fig. 13a). As can be seen, a variation of duty cycle will cause a variation in the d-c level of the unblanking pulse (Fig. 13b), which will cause the signal to defocus, or to "bloom," if the sweep rate is increased for a closer look at a signal, or the trace may disappear if the sweep rate is decreased for an over-all look at a sequence of events.

Christaldi (*52*) met this situation head-on by using a separate, bistable multivibrator, which operated at the d-c level of the CRT cathode, to provide the positive unblanking voltage. Consequently, the unblanking signal could be d-c-coupled to the grid of the CRT, and duty-cycle or long-time *RC* distortion effects would thereby be avoided. The differentiated waveform from the sweep-generator-gating multivibrator is used to initiate and terminate the unblanking voltage, thus providing positive duration control at all sweep rates (see Fig. 13c). Providing enough current to obtain rapid unblanking at the high negative voltages of most CRT cathodes can present a difficult power-supply problem. Also, when the instrument is turned on, the multivibrator may turn on in the unblanked state, although when the sweep generator commences to operate, it will correct the situation. However, this latter situation might be overcome by designing the circuit so that one side is biased more heavily than the other.

Kobbe (*53*) solved this problem in a rather unusual manner. He simply added a high-voltage d-c power supply between the grid of the CRT and the cathode follower which drives it with the unblanking signal. The

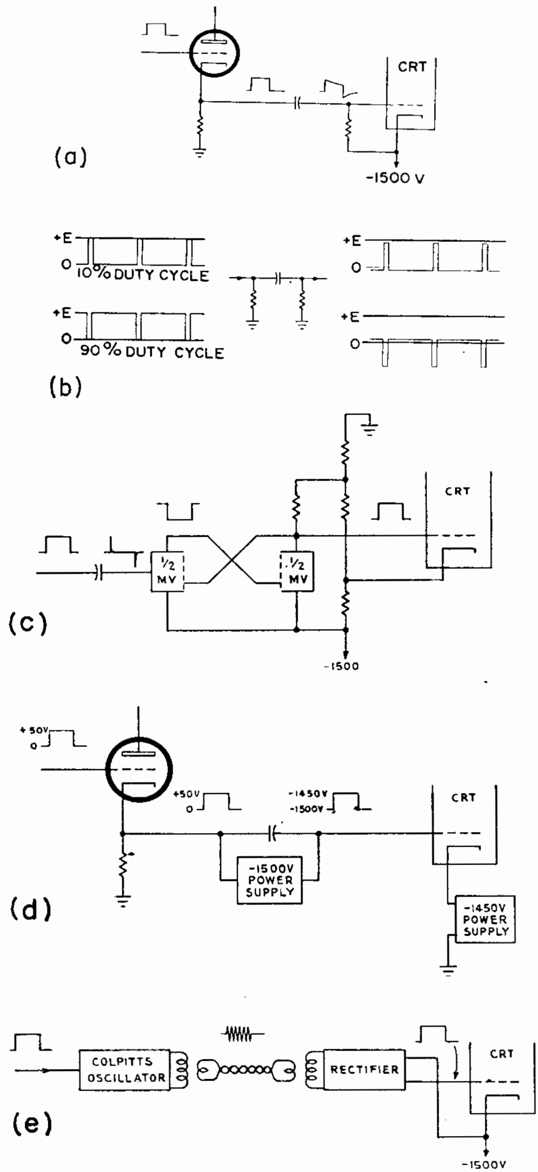


FIG. 13. Methods of unblanking the CRT. Method (a) will result in a variation in intensity on the trace on long sweeps; (b) illustrates the problem when the time constant of the coupling circuit is long compared with the unblanking waveform. If (e) is a level necessary to obtain satisfactory unblanking, the upper waveform will give just barely satisfactory performance, whereas the lower one will not permit any trace at all; (c), (d), and (e) all illustrate methods of coping with the problems represented in (a) and (b).

positive end of the power supply is connected to the cathode follower, the negative end to the grid of the CRT (see Fig. 13d). The d-c voltage of the supply is approximately equal to the potential of the CRT cathode. (Actually, it is set a few volts negative to the cathode to cut off the electron beam.) The operation is at once apparent. If a positive 50-volt square pulse is applied to the cathode follower, the grid of the CRT also rises 50 volts, but at a potential which is some hundreds or thousands of volts negative. Suitable frequency-compensating circuits extend its capabilities to very fast-rising, short-duration, unblanking pulses.

Vollum (unpublished) devised an interesting circuit to maintain uniform brightness on long sweeps;[12] this circuit was used in conjunction with the phantastron sweep generator and made use of the positive square gating signal appearing on the screen of the phantastron tube for controlling the operation. This voltage was used to gate the operation of a Colpitts oscillator, which was inductively linked, via a twisted pair transmission line, to a tuned circuit paralleled by a diode rectifier or detector (Fig. 13c). Whenever the oscillator was activated—which was during the quiescent period of the sweep generator—a negative dc potential was developed by the rectifier circuit and impressed on the CRT grid. While the sweep generator was operating, of course, the CRT was unblanked. Although the circuit is excellent for relatively slow sweeps, it lacks short-time capabilities and is no longer used.[13]

H. Magnification

Many times a more detailed examination is desired of a particular part of a display, but because of signal intricacy, it may not be possible to initiate the sweep immediately prior to the desired portion, in order to view it at a faster rate with the consequent expansion of detail. In such a case, some kind of display magnification is desirable. Magnification can be obtained in a number of ways. One common method is accomplished by increasing the gain of the horizontal amplifier (see Fig. 14a). Unfortunately, this usually results in a loss of bandwidth, and consequently a loss of timing information.

1. "Calibrated-Gain" Magnification. Moulton and Ropiequet (*51*) contributed a solution to this problem with a stabilized-gain d-c amplifier, in which the amount of degenerative feedback can be varied in precisely controlled steps. Controlled feedback permits the degree of magnification to be as accurate as the circuit components forming the attenuator-type feedback circuit (see Fig. 14b).

One of the noteworthy features of this circuit is the provision for identifying the magnified portion of the trace. The voltages can be

[13] Schmitt (*54*) described a similar circuit for use in medical work. This technique has been used quite widely in that field for d-c isolation.

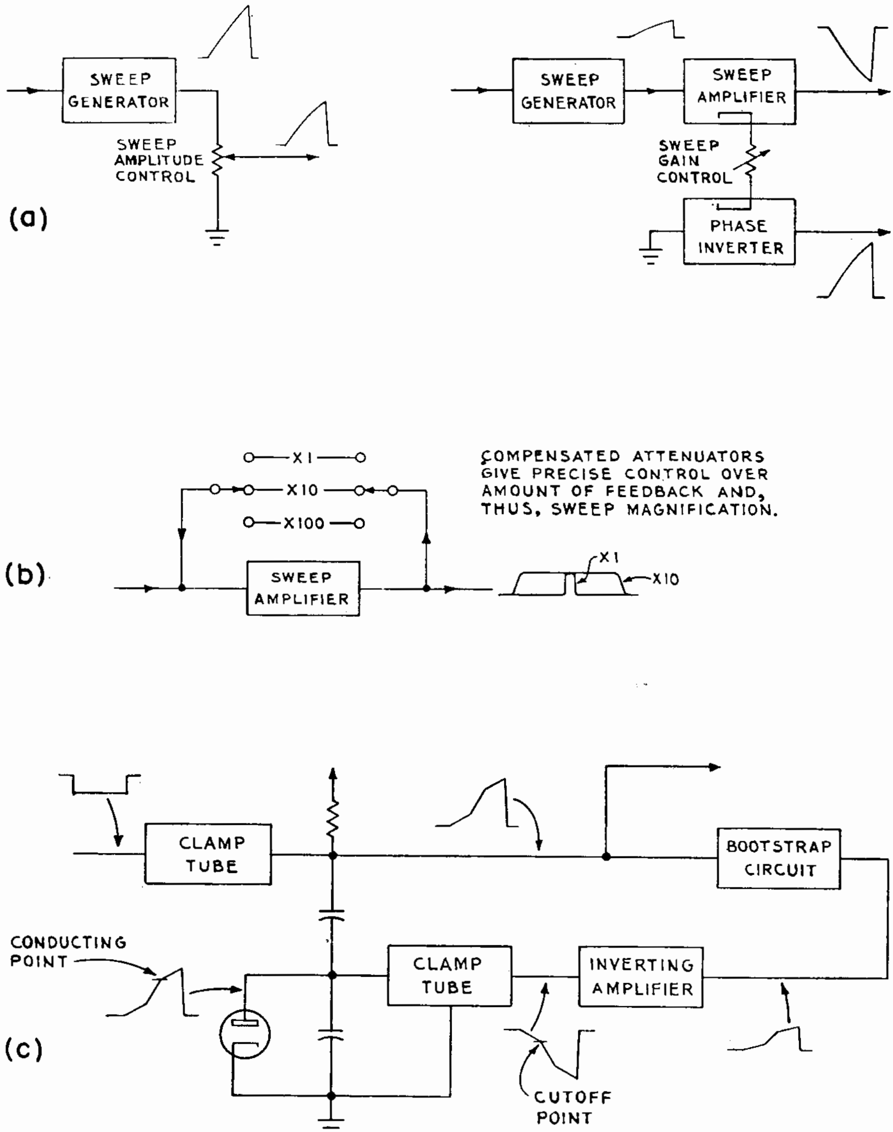


FIG. 14. Methods of magnifying a sweep waveform. (a) Some early sweep-magnifying systems. (b) Variable-magnification sweep amplifier (Moulton and Ropiequet (*51*)). (c) Notch-type sweep amplifier. In the methods illustrated in (a) distortion of the waveform will occur because of a change in the capacitive component of impedance or a change in the operating characteristics of the tubes caused by the operation of the "magnifier" control.

adjusted so that corresponding points on the regular and magnified traces coincide at some particular point on the screen. Usually this fixed point is selected to occur at the center of the screen, so that magnification takes place equally on either side. As can be seen, this retains the timing information and permits rapid selection and identification of the desired portion of the signal.

Several firms are now using this type of horizontal amplifier in their commercial instruments. It is a relatively simple and accurate means of expanding the time axis of the oscilloscope without the complication and expense of a separate sweep generator. Magnifications of 100 or more can be obtained, although the circuit can do no better—that is, the sweep can travel no faster—than is permitted by the basic design of the final amplifier. By one design standard this is 5 times the rate of the highest regular sweep rate. Thus, if this latter is 0.1 μsec/cm (this seems to be the upper range limit of most high-performance, general-purpose instruments), a magnified rate of 0.02 μsec/cm is available.

2. "Notch" Magnification. Another technique which has been developed to solve the magnification problem uses a "notch" to display the expanded portion of the signal. A portion of the sweep waveform is speeded up by some desired factor, but both the regular and the magnified sections are displayed by the same trace (*55*). This permits very rapid selection and identification of a desired portion of the sweep.

Basically, the method used to expand the desired portion of the sweep involves increasing the amount of charging current through the sweep-generator circuit for a given period of time. Since the rate of voltage change (which determines the sweep rate) varies directly as the charging current, the problem is to develop a method of controlling the rate of charging in the sawtooth generator.

One circuit which uses this type of sweep expansion is designed around the bootstrap sweep generator (see p. 11 in ref. *46*). The capacitive portion of the timing circuit contains *two* capacitors in series, with a clamp tube in parallel with one of them. This clamp tube is normally conducting, so that the effective circuit capacitance is that of the other capacitor. However, the circuit is arranged so that the clamp tube becomes nonconducting when the sawtooth reaches a desired voltage. This decreases the circuit capacitance, which increases the rate of charging which increases the sweep rate. As the sawtooth voltage continues to increase at this new rate, it reaches a point which brings a diode into conduction and this again reduces the circuit capacitance to that of the original capacitor. The sawtooth then continues to increase at the original rate until the whole operation is terminated by the gating signal which initiated the cycle (see Fig. 14c). Of course, methods of controlling the initiation and termination of the fast portion permit examination of any portion of the trace. This circuit is a relatively simple, reliable, and stable method of developing an expanded portion of a sweep.

1. Two New Sweep Circuits

During the period 1950–1952, Ropiequet (*50*) developed a sweep circuit that has proven to be the conceptual basis of most subsequent high-performance sweep systems. Even though this particular circuit is no longer used and the derivative circuits have been modified and simplified, it marks the first significant change in sweep-circuit concept, and for that reason should be described in some detail. While most of the various circuits elements were well known and had been in existence for some time, the configuration reveals a totally different philosophy of timebase operation then heretofore.

The change resides in the use of the feedback loops described earlier. To illustrate the difference, a comparison between several of the prior circuits and the new one, called the "315 circuit" for convenience, will be revealing.

The several major types of sweep circuits which existed prior to this circuit have been well described in many publications (*6*, *7*, *56*) (see Fig. 15a, b, c, and d). They can perhaps be described as "straight-through" types, because of the basic sequence of operation, and their functional diagrams show little difference in conception. Circuits have been added to provide better control of the duration of the sweep; to permit the single sweep operation; to linearize the sawtooth, etc., but only in a linear or sequential fashion. (Note also the change in the idea of intensity modulation—from blanking the return trace to unblanking during the sweep.) On the other hand, the 315 circuit, while not including many new circuit elements—the Schmitt trigger is the only major addition—did incorporate many more circuit elements, arranged in feedback loops, similar to those discussed in connection with the hold-off circuit and the sweep generator (see Fig. 16). These circuits do not control the circuit performance in the sense that a feedback loop in a servo system does—that is, to modify the input information to compensate for errors in the output performance—but rather in the sense of a logical circuit; that is, "if *A*, then *B*," or "when *A*, then *B*." The hold-off circuit says, in effect, "The input is to remain open until the multivibrator changes from State *A* to State *B*, when it is to close. When the multivibrator changes from State *B* back to State *A*, the input is to be opened a predetermined time later."

The sweep generator is controlled by a slightly different type of logical circuit. In effect, its says, "If the multivibrator (MV) changes

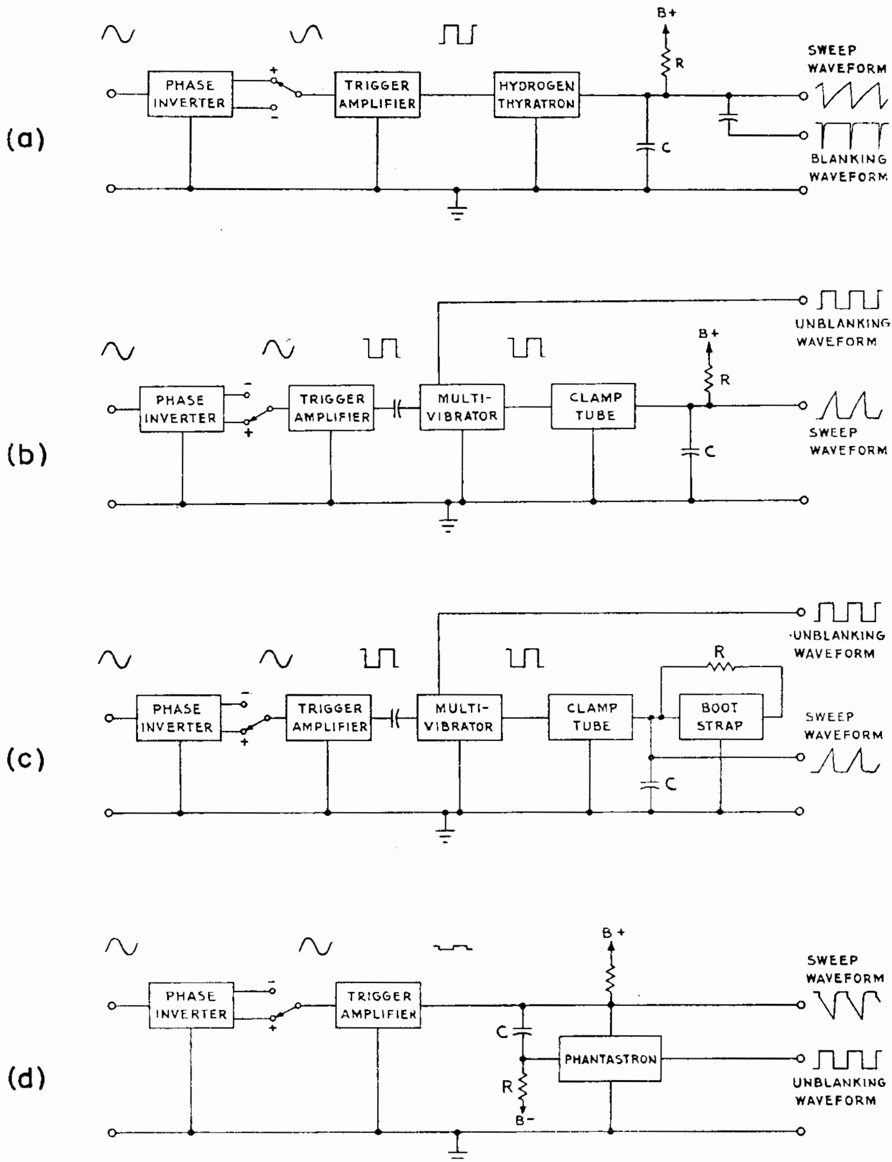


FIG. 15. Several widely used sweep generators. These can be called "straight-through" circuits because each stage depends for its operation on the action of the stage before it. There is no influence exerted on earlier stages by the action of a given stage such as that suggested by Figs. 11 and 12. (a) Thyratron-controlled *RC* sweep generator. (b) Multivibrator-controlled *RC* sweep generator. (c) Multivibrator-controlled bootstrap circuit sweep generator. (d) Phantastron sweep generator.

from State A to State B, then the sweep generator is to progress from State E_0 toward State E_b. When the sweep generator reaches predetermined State E_z, the MV is to reset to State A, which returns the sweep generator to State E_0.

As can be seen, a very stable cycle of operation will result from this circuit, and each succeeding cycle will be equally stable. If the output

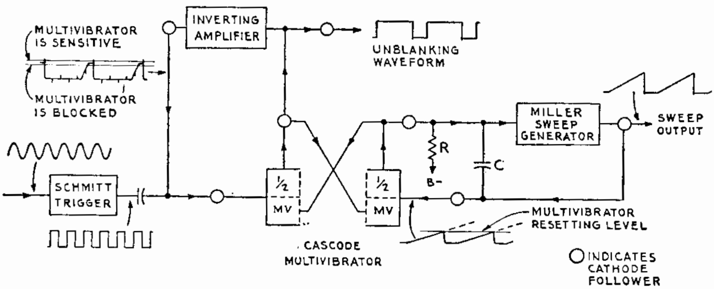


FIG. 16. The use of logical circuits to promote stability and accuracy of operation. Many cathode-followers are used for coupling and isolation. The resetting level can be varied to vary the sweep length. (The multivibrator is composed of two cascode amplifiers (*57*), and is sensitive to tube aging effects.)

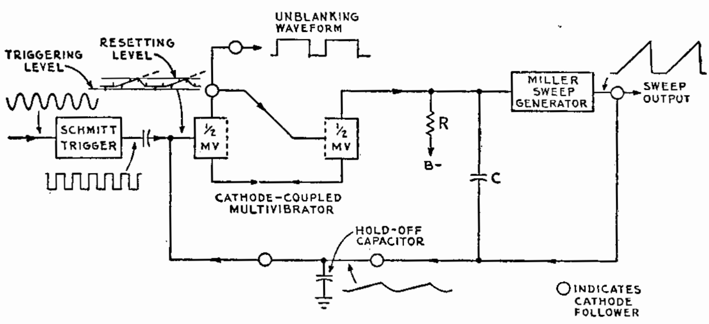


FIG. 17. This circuit combines the performance capabilities of the Ropiequet circuit with great simplicity and consequent reliability.

of a Schmitt trigger circuit is fed to the input of this circuit, a sweep system is obtained which permits viewing very fast-rising pulses, slow changes in d-c level and nearly anything in between. Very complex waveforms can be easily examined in rather minute detail because of the possibility of starting the sweep at practically any point of the signal.

Kobbe suggested a modified and simplified circuit that was in improvement in several ways on the Ropiequet circuit (see Fig. 17). One of the major changes was that the multivibrator was changed from a cascode design to a cathode-coupled design. While the cascode circuit offers many advantages over the conventional type of multivibrator (*57*), it is sensitive to aging effects in the tubes, and for that reason proved to be somewhat less satisfactory. Both circuits use cathode-follower coupling between the plate of the input portion and the grid of the output portion to shorten the transition time. Kobbe's circuit used cathode coupling to complete the regenerative feedback path in preference to the ordinary method of MV coupling.

The coupling between the multivibrator and the sweep generator in the Ropiequet circuit is accomplished by means of a cathode-follower pentode clamp tube; Kobbe clamped directly, by means of a diode. The Ropiequet sweep had two separate feedback loops—as described earlier—one in the input portion to block any further trigger signals from affecting the multivibrator and one in the sweep generator circuit to reset the multivibrator: Kobbe combined these into one, using the sweep waveform to unblock the input to the multivibrator and also to reset the MV. Quite a drastic reduction in the number of tubes was made possible by this change, with a consequent improvement in reliability. The circuit has a sweep time range of 6×10^8 to 1 (from 120 sec to 0.2 μsec).

J. A Delayed-Sweep System

No matter how accurately the sweep generator operates, the accuracy of measurement is limited by the measuring method used. In most cases this is simply visual observation by the user. It will be appreciated that on a 3- or 5-in. CRT screen, it is difficult to estimate a measurement to within 1 or 2% and then only by close observation. A magnifying glass may be used, but the graininess of the phosphors limits definition to about 0.2% on a 5-in. screen. A better method is to magnify electronically the section of the sweep desired, and several methods of doing this have been discussed already. In addition to these, there is another way which, while much more complex, allows a wide range of additional capabilities to be had. (This system has been dealt with quite extensively in the M.I.T. Radiation Laboratory Series: see refs. *58*, *59*, and Sect. 7.6 in ref. *55*.)

Suppose that we wish to examine a small section of a display in great detail. If it were possible to trigger the sweep at that precise point of the display, we could use any sweep rate obtainable and expand that part of the display as much as we desired. We have discussed a trigger circuit that is exceedingly versatile, but there are a number of signal conditions that could inhibit our selection of just the portion we wished, i.e., a slope and voltage level identical to the one we desire, but occurring just prior to it. However, let us provide a second sweep circuit in the same instrument, and with the same triggering capabilities as the first one. As we have seen, the Schmitt trigger circuit will permit us to obtain a trigger signal at a given voltage level, no matter what the rate of voltage rise (see Fig. 18). Consequently, we can trigger sweep circuit *B* from the sweep waveform *A* and obtain a range of variation in the occurrence of *B* which depends only upon the duration of sweep *A*. If we arrange some means of indicating the position of sweep *B* with reference to *A*—such as brightening the trace for the duration of *B*—it will be seen that we now have a means for selecting and viewing any portion of a complex waveform. We need only display the over-all cycle, select some portion we wish to examine in greater detail, move the sweep *B* to that particular portion,

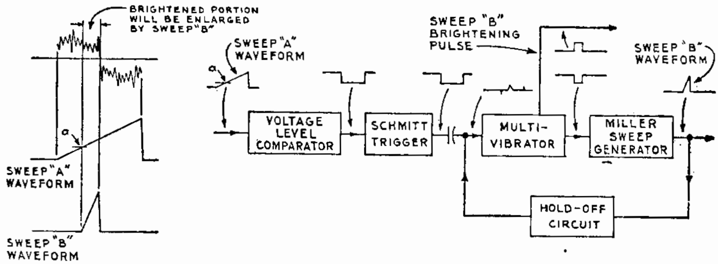


FIG. 18. A circuit to permit magnified examination of a small segment of a display. It should be emphasized that this is a second sweep circuit which is triggered from the sawtooth voltage of a primary sweep generator. Switching permits the output of this circuit to replace the output of the primary circuit, giving a delayed, and "time-altered" (magnified or demagnified) display.

and then by properly arranging the switching circuits, transfer the sweep waveform *B* to the horizontal amplifier of the instrument and adjust the sweep rate to give us a suitable expansion. The expanded portion of the signal will appear on the screen.

There are certain types of signals which cannot be seen clearly even with this type of viewing system. Consider a multichannel communications system which codes information by varying the time position of a pulse about its expected occurrence at some particular repetition rate, in other words, a pulse-time modulation system. If viewed by the above system, one would only see a blur whenever information was being transmitted on any particular channel (*60*). However, a change in circuitry will permit us to examine the individual pulses used in even this type of signals system (see Fig. 19).

Rather than trigger sweep generator *B* directly from sweep waveform *A*, let us insert a bistable or arming multivibrator between the triggering circuit and the multivibrator of sweep generator *B*. Let this arming multivibrator be able to be triggered by either the trigger circuit output or the resetting phase of the sweep multivibrator waveform, depending upon the state of the arming circuit. Let the circuit connection be such that when the arming multivibrator is sensitive to the trigger signal, it blocks the input to the sweep *B* multivibrator; when the arming multivibrator permits sweep *B* multivibrator to be triggered, it is sensitive to the sweep *B* multivibrator-reset signal.

Under these conditions, the basic repetition rate signal can be used to trigger sweep *A*; this in turn will trigger the arming multivibrator after

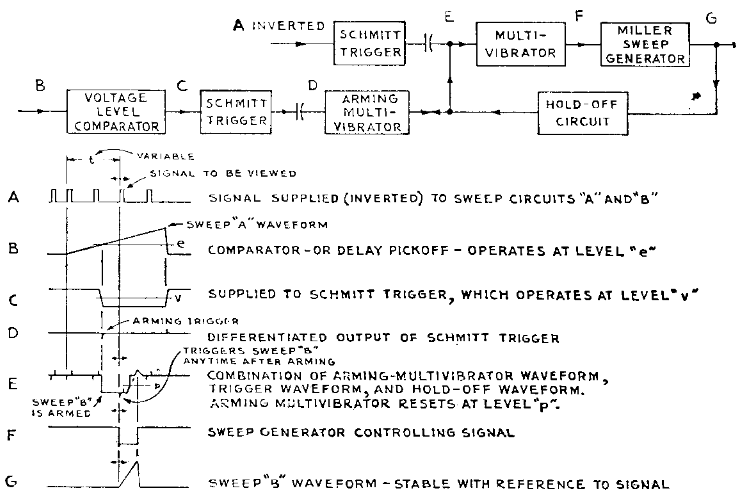


FIG. 19. This circuit permits the "viewing" sweep to be delayed a given time and then triggered by the next signal occurring after this period. Unlike the circuit in Fig. 18, this circuit requires a signal for the "delayed" sweep to operate. It can be converted to the type of operation possible with the circuit in Fig. 18, or to permit only one sweep, by adjusting the operating characteristics of the arming multivibrator.

a period of time determined by sweep *A* waveform and the setting of the voltage-level comparator; sweep generator *B* is then armed by the arming multivibrator; the *next* signal received triggers sweep generator *B*, which in turn resets the bistable multivibrator, and when sweep *B* comes to an end, no further cycles of operation can occur until sweep generator *A* has reset and can be triggered again.

Simple circuit rearrangements can be made which permit sweep *B* to trigger from sweep *A* or the displayed signal, which permit manual "arming" of the "bistable" multivibrator when sweep *A* is disabled, permitting only one cycle of sweep *B* whenever a signal occurs. With careful design, the time instability of sweep *B*, when initiated by sweep *A*, be as low as 1 μsec at a delay of 50,000 μsec, and 1 μsec at 20,000 μsec delay is easily obtainable. Incremental measurements of time, referred to sweep A, can be made to an accuracy of better than 0.2%.

V. General Improvement

While a great deal of effort has been spent upon the design and development of new circuits and tubes in recent years, at least as much effort has been directed toward the improvement of the other aspects of the cathode-ray oscilloscope. The over-all result has been a general upgrading of all test equipment, wherein features which formerly were obtainable only on special order at great cost are now expected to be included as a part of practically everything other than the cheapest home workshop equipment.

Much of the impetus for this improvement has come from experience with electronic equipment during World War II. Many of the present instrument engineers made their first acquaintance with such equipment in the military service and, while impressed by the best of it, were appalled by the worst of it. The influence of this experience could be seen almost immediately in scattered instances of postwar electronic instruments, permeating nearly every aspect of design, from the mechanical through the electrical to the physical.

Several of the problems calling for solution were interlocking. For example, the large and increasing quantities of components used in much electronic equipment posed at least two serious problems. One was the obvious need for more reliable components and designs to avoid frequent failures in operation. Equally important, but more pressing because of the difficulty of solving the first problem, was the requirement for easy serviceability. (Many readers will recall working for several hours in extreme physical discomfort to replace one defective component in an inaccessible location.) Consequently, much postwar effort was directed toward improving physical layout so as to reduce the servicing effort to a minimum. The positive and negative influences of military-equipment design began to be evident.

To cite a few examples, it is now fairly common practice to orient the various chassis so that the wiring and components are exposed. (In a hidden location, it is much easier to change a tube than to replace a defective capacitor or resistor.) When enclosed areas are unavoidable, chassis are usually hinged or designed to be easily withdrawn. Tube sockets, resistors, capacitors, and other components are identified with their type numbers, circuit designation, or both. The advantages of these improvements where servicing is concerned are immediately apparent.

An additional bar to easy serviceability has long been the "rat's nest" of wiring which most underchassis views revealed. Tracing circuits, finding the desired component, and restoring a replaced part to its proper place in such situations was rather unnerving to the average maintenance person.

In the interests of keeping the instruments performing at their peak efficiency, it was felt that a rearrangement of the various parts was definitely called for. A prewar technique that has gained wider application in postwar equipment is the mounting of components on bakelite or fiber boards, which have metal posts or clips fastened into them at convenient intervals. These are placed adjacent to a row of tube sockets, which are connected to each other and to the component by direct point-to-point wiring. In this way, stray capacitances are kept low and fixed. The various voltage distribution conductors have been collected and "cabled" in neat laced bundles or "harnesses," and the individual conductors are now coded to aid in tracing their paths.

The drive to reduce the size and weight of instruments has resulted in a number of further changes in wiring and component mounting techniques (*61*). One problem with the mounting boards is that they require a certain amount of chassis area which cannot be used for anything else (except for mounting certain types of components on the other side). This situation is partially solved by standing boards on edge, but the ease of service-ability is then decreased.

One firm has contributed a solution that makes use of a mushroom-shaped "turret" fastened to the underside of the tube socket (*62*). This has the very great advantage that most of the components associated with a particular tube can be mounted directly at its base.

The National Bureau of Standards has developed a series of small square ceramic wafers with metallized notches in the edges (*63*). With the aid of resistive tapes, metallic inks, etc., most circuit components can be duplicated on a wafer and several of these can be mounted in a stack, supported by the circuit conductors. These, in turn, can be mounted on one tube socket, and a great saving in space results.

R. J. Davis and M. Goodfellow (unpublished) have designed some small wedge-shaped ceramic strips with metallized notches in the thin edge.[14] When these are mounted in rows on each side of a row of tube sockets, it is possible to mount components directly over the pins of the sockets, permitting very short leads and again a saving in space.

A technique which possibly holds the greatest promise for space saving is the one called "printed wiring." It has the disadvantage that it does not permit easy modification of individual instruments, but this is of little consequence in high-volume production, where modifications in

[11] Components used in Tektronix equipment. During the preparation of this volume, U.S. Patent 2,836,807 was issued on the Davis-Goodfellow work.

design can be scheduled periodically. Even though most oscilloscope manufacturers produce in limited quantities, several of them are using the printed-circuit boards in their equipment.

A. Component Design Problems

The performance of a number of the newer circuit configurations has aggravated problems which were tolerated a few years ago. Several examples will illustrate some of the problems and solutions.

Since a Miller integrator is essentially a high-gain d-c amplifier with a degenerative a-c feedback path, it can be seen that for long cycles (10 sec and over) stability is a prime factor. One of the more important components contributing to stability is the capacitor which constitutes the feedback path. This has a linear, but inverse, effect upon the rate of voltage change of the sweep sawtooth. Naturally, constancy of capacitance is of great importance to the timing accuracy.

Before the general use of the Miller generator there was little need for capacitors to be selected with an accuracy of better than 1%. Selection was usually made from standard commercial units. However, the new levels of accuracy permitted by the Miller circuit made it desirable to match sets to ¼% tolerance. Outside of the increase in tedium involved in selection and matching, the temperature coefficients and the dielectric losses rendered these tolerance figures meaningless.

One acceptable solution to this problem was to manufacture special capacitors to meet these requirements. The use of Mylar film dielectric, silicone impregnation in vacuum, and other advanced materials and techniques enable the tolerances to be met. Composing all capacitors of two or more units and matching errors results in finished products of exceptional stability and reliability.

The wide-band performance capabilities of some of the newer amplifiers has accentuated many of the design problems associated with these circuits. The signal-delay network furnishes an excellent example of this situation.

By the very nature of the techniques used in an oscilloscope, a signal which triggers a sweep circuit cannot be completely delineated by the sweep circuit. No matter how sensitive or fast-acting the circuits are, any signal will be partially over by the time the trace is visible and the sweep is operating linearly. For signals of milliseconds duration or longer, it does not greatly matter, but as the signal duration approaches a microsecond or less, a substantial portion of the signal will have passed before the instrument begins to display it.

This situation has been solved by delaying the signal, after it has been sampled for starting the sweep circuits, but before it arrives at the vertical deflection plates. This gives the sweep and unblanking circuits time to become fully operative before the signal appears.

The signal-delay problem in oscilloscopes has generally been solved by the use of high-impedance delay cables or lumped-constant transmission lines. In spite of the attractive simplicity of a piece of cable, we find that the lumped-constant circuit produces a more faithful response to the original signal. The reason seems to be that the artificial line can be adjusted at every point for optimum response, whereas the cable can be adjusted only at the input and output. Commercially available cable apparently has minute variations in its characteristics which become serious at video frequencies and which cannot be removed by adjustment.

The use of the distributed amplifier has increased the frequency requirements of delay networks, which means an increase in the number of individual delay sections (*64*), and a consequent adjustment and manufacturing problem. However, the physical and electrical forms of both the distributed amplifier and the delay network are quite similar, and it is advantageous to design the two as a unit. In fact, termination considerations make it expedient to omit the resistance termination of the delay network at the deflection plates of the CRT and design the circuit so that the deflection plates form one additional section of the delay line. This arrangement has the apparent disadvantage of requiring a push-pull delay network with its added cost. However, it was found that a common capacitor could be used for both halves of one push-pull section, both in the delay network and the amplifier, and since each T section affects only one specific time portion of a signal, the adjustment of the delay lines is much simpler than would be expected. In other words, if a step function is being viewed on the oscilloscope and a capacitor in the delay network is changed, only one rather sharply defined section of the signal will be affected, at a time determined by the position of the capacitor in the delay network. If another capacitor (either before or after that one) is adjusted, the signal will be affected either earlier or later, respectively, than in the previous case (see Fig. 20).

The lack of a terminating resistance at the CRT end of the delay line has one very great advantage over the usual practice of terminating the networks at both ends in their characteristic impedance. This advantage is that the signal amplitude is doubled, which is no small consideration when working at wide bandwidths.

However, it will be appreciated that the remaining termination for the distributed-amplifier delay line combination must be nonreactive in the highest degree to avoid distorting reflections of fast transients. The ideal situation would be to extend the distributed-amplifier plate network "infinitely" between the first tube section of the amplifier and

$B+$. A resistive termination "looks" like an infinite line to a signal and under optimum conditions will completely absorb the signal. However, many resistors have inductive or capacitive characteristics which become noticeable at frequencies above 10 Mc, and consequently are unusable as termination resistors in distributed amplifiers at those frequencies.

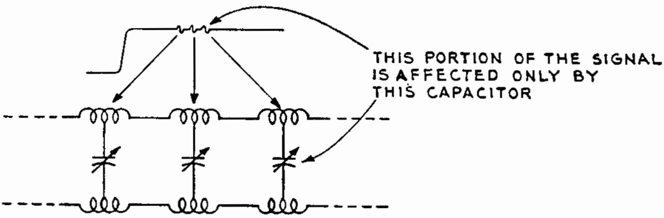


FIG. 20. Individual sections of a lumped-constant delay network will affect discrete portions of a step function passed through it. This considerably simplifies tuning and permits optimum response to be obtained.

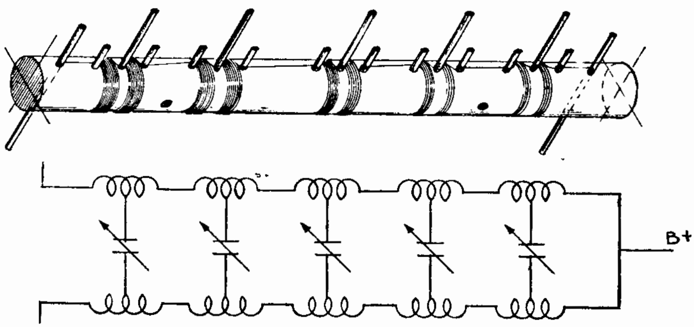


FIG. 21. Terminating network for high-frequency, distributed-amplifier plate network. Designed to operate in a push-pull circuit, this network requires two specially designed resistive inductances of the type shown. Its unique character is a result of using resistance wire for winding the inductance and of "tapering" the amount of resistance and inductance by varying the number of turns of the individual sections. The value of the shunt capacitance varies inversely as the inductance, being designed to make the frequency response—or the time delay—of each section the same.

Kobbe (unpublished) suggested a solution which was, in effect, a "synthetic" resistance.[15] He designed a network which is a continuation of the artificial delay line in the plate circuit of the distributed amplifier. The unique feature of this network is that the inductive portion is wound of resistance wire. The total resistance of the network is made equal to the impedance of the plate-circuit delay line, and this characteristic determines the total extent of the termination. The first T section of the

[15] Component used in Tektronix Type 540 Series equipment.

termination is designed to have approximately the same characteristics as the individual T sections of the amplifier delay network. However, a portion of the total resistance has been "used up" by the resistance wire contained in the inductance of the T section, and a signal at this point would "see" a lesser termination resistance, which then must be matched by the impedance of the next T section. As can be seen, this design gives the network a "tapered" character, with the impedance at any point looking toward B+ equal to the remaining resistance. While this theoretically requires an infinite number of T sections, in practice it is found that the impedance—and consequent signal level—can be reduced in four sections to such a low level that the distortion introduced by a single additional final T section is undetectable (see Fig. 21).

B. Isolation of Stray Capacitance

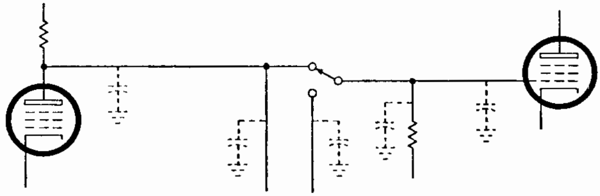
The distributed amplifier might be said to embody the concept of electrically separating a number of capacitive elements, in order to reduce the capacitance that a signal will "see" at any given point. This concept has been useful in improving the performance of some high-frequency circuits. For example, many times in a circuit, several leads will come together at one point—leads carrying positioning voltages, plate and grid connections of an interstage coupling, etc.—and in addition to the electrical functions of the leads, they also introduce stray capacitance into the junction. Normally, these "strays" add up to one lump sum, with a consequent deterioration of the high-frequency response in the circuit. However, if they can be separated as shown in Fig. 22, the upper frequency limit of this portion of the circuit can be substantially improved (doubled or tripled in some cases). Essentially, the circuit assumes the character of a lumped-constant-delay network.

C. A New Probe

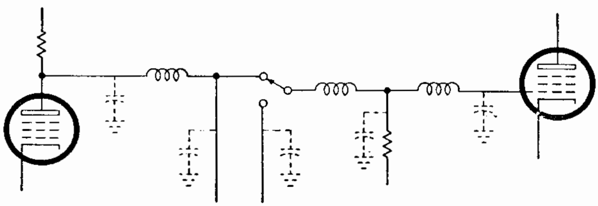
The wide-band performance that can be gained with the above techniques revealed an inherent problem in signal pickup which had not been noticed previously because of the limited response of prior amplifiers.

One of the most critical problems in the handling of information is the method of detecting it, that is, the method of transferring the signal from the signal source to the measuring device. Many methods exist, but each situation requires a method appropriate to the circumstances of that situation. The factors involved include such things as the character of the signal (risetime, frequency components, amplitude, etc.), the character of the signal source (mechanical, electrical, chemical, impedance, etc.), and the character of the measuring instrument (in this case the oscilloscope). The ideal transfer would be one in which the character of the signal is not changed in any way.

However, few signals arise from sources which will enable us to reach out and just "clip-on" (completely aside from any types of signals that may require a transducer for detection). Most electrical or electronic



STRAY CAPACITANCES THAT TEND TO DETERIORATE HIGH-FREQUENCY RESPONSE



DELAY-LINE" METHOD OF ISOLATING STRAY CAPACITANCE

FIG. 22. A signal will be deteriorated by the total amount of stray capacitance that it sees at any given time. If the total capacitance consists of several discrete "bits" physically separated from one another, small inductive elements can be used to separate them electrically from one another, as indicated in the above diagram. The bandwidth of the coupling circuit will then be determined by the bandwidth of only one of the "sections."

signal sources have characteristics which will cause a change in the signal if some pickup device is attached to them. In other words, we need to isolate the signal source from the deteriorating effects of the measuring instrument and the coupling method. This nearly always involves attenuation of the signal by whatever method it is accomplished. Of course, we may need to attenuate the signal, and in this case, our problem is to design attenuators which will be uniform in their response over the whole range of frequency response, and which keep the input impedance of the instrument constant no matter what degree of attenuation is used.

The techniques of doing this are well-known and need not be repeated here (*65*).[16]

In most cases, the input impedance of oscilloscopes is designed to be 1 to 2 megohms, shunted by 20 to 45 $\mu\mu$f. To many signal sources, this represents a substantial change in characteristics and consequent deterioration of the signal. To avoid this, the input impedance can be pushed considerably higher—say, 10 mg—and the capacitive shunting can then be reduced to 10 or 15 $\mu\mu$f. This change constitutes an attenuator and the consequent reduction in signal amplitude is a result.

A standard technique has been to include the extra resistance and series capacitance which is needed to make this change in a probe which is mounted at the end of a convenient length of coaxial cable. The problem appeared when these probes, which are in general use, were used with amplifiers of extra bandwidth capabilities. The length of the probe cables, the propagation velocity of the cable, and the frequency response of the amplifier all were of such a value that a "tuned-circuit" effect was evident at frequencies well within the range of the amplifier. Consequently, the system became useless for precision measurements in the vicinity of certain frequencies.

One method which has been used to decrease the sensitivity of a circuit to critical frequencies inserts some low-value resistors in the circuit at critical points to damp out any incipient oscillations. However, that method did not work in this case. Kobbe (unpublished) suggested that the regular center conductor of the coaxial cable be replaced with a resistance wire which would be of such a value that no oscillations could build up.[17] The value must be computed for each probe length and attenuation ratio. It permits the amplifier to be used to its full bandwidth.

D. Nonreactive Load Resistors

A number of schemes exist for reducing the reactance of wire-wound resistors, which are often necessary as load resistors for high-frequency amplifiers (*66*). However, even the small residual reactance of some of these resistors can not be tolerated in certain oscilloscope amplifiers. As an example, one noninductive design, which consisted of two parallel but counterwound coils of resistance wire, was found to deteriorate the high-frequency end of the frequency response below what was necessary for the projected performance. A specially fabricated, mica-card (*66*) design

[16] Nearly any oscilloscope instruction manual will illustrate the methods used to obtain an attenuation range of 40 or 60 db. See manuals of Allen B. DuMont Laboratories, The Heath Company, Hewlett-Packard Corporation, Tektronix, Inc., and others.

[17] Technique used in 400 Series probes manufactured by Tektronix.

increased the 3-db point of the passband from 8.5 to 12.5 Mc, which was great enough to accomplish the desired goal. An Ayrton-Perry (*66*) design, which consists of parallel counterwound resistors on a thin mica card, improves the performance even more.

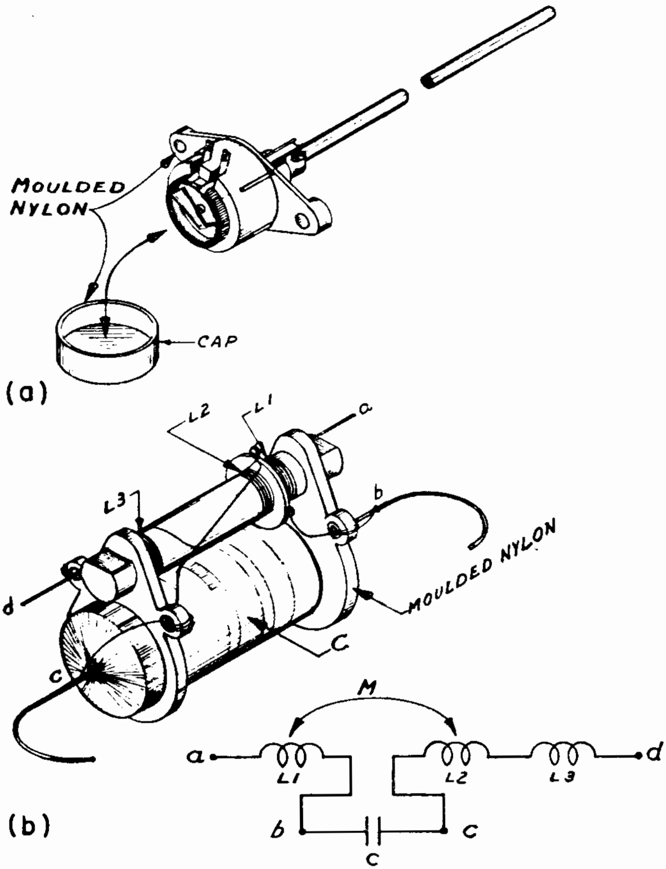


FIG. 23. Much of the improvement in oscilloscope performance has been due to devices which permit circuits to perform more closely to their theoretical limits. Two such devices are illustrated here. (a) Low-capacitance rheostat. (b) Four-terminal coupling network.

A somewhat different problem called for a rheostat which needed a small but finite *ratio* of inductive reactance to resistance, which would remain fixed as the resistance was varied. The solution was to wind the resistance wire on a strip of insulating material whose thickness determined the amount of inductance (see Fig. 23a).

Many additional gains in performance have been made possible because skills and tools have often been available which permitted the development of special components and fixtures incorporating the exact characteristics necessary to obtain optimum circuit performance. Consequently, it is found that many oscilloscope manufacturers are expanding the types of development and production activities in which they engage, even though they are not directly concerned with oscilloscope design. In addition to the rheostat, there have been such devices as the four-terminal interstage coupling network pictured in Fig. 23b. In this case, the electrical components are held in precise and reproducible relationship to one another.

E. Power-Supply Design

Much of the recent improvement in oscilloscope performance is due to improvements in the d-c voltage supplies of the instrument as well as in the amplifiers, timebases, and components. The widespread use of electricity works to cause wide variations and fluctuations of the stated power-line voltage at the point of consumption. For any degree of measuring accuracy, these conditions can be fatal.

Consequently, electronically regulated power supplies are now standard equipment in nearly all high-performance oscilloscopes and compensate for transient or long-time variations of line voltage as well as variations in current requirements caused by load changes. The voltage control is established by comparing the output voltage of the power supply with a reference voltage established by one of the newer, voltage-reference tubes, such as the EIA Type 5651. Voltage variations can usually be held to less than 0.1 volt at a level of 200 or 300 volts. In critical circuits, even the filament voltages can be regulated, which decreases the noise level, as well as stabilizing the tube emission characteristics.

Many oscilloscope power supplies use metallic rectifiers rather than vacuum rectifiers. Since no filaments are involved, fewer transformer windings are necessary, less power is consumed, less cooling is necessary, and consequently the reliability of the equipment is improved.

The high-voltage power supply for the operation of the CRT has been improved considerably also. Few instruments now use the "brute-force" type of supply, where the 60-cps line voltage is boosted to several thousand volts. Aside from the practical difficulties of regulation, the danger to personnel is acute during "hot" servicing. Most instruments now use either a pulse-type supply or a high-frequency type. The pulse type (such as are found in television sets) depend upon a periodic pulse to shock-excite a tuned circuit, whose output is then rectified, filtered, etc. The high-frequency or RF-type supply obtains its energy from an oscillator operating somewhere in the range of 5 to 100 kc. The primary of the high-voltage transformer is a portion of the tank circuit of the oscillator. The secondary circuits are quite conventional except for the feedback tap which samples a portion of the output voltage, compares it with a standard voltage, and adjusts the operation of the oscillator to compensate for any changes. The advantage of the high-frequency type of circuit is that smaller components, both in physical size and electrical characteristics, can be used than are required at 60 cps to obtain adequate filtering and regulation. Since the currents involved are much smaller, the hazard to life is lessened also.

VI. Operational Features

A number of techniques have gained wide acceptance in the last few years to increase the utility and versatility of cathode-ray oscilloscopes to the users. Most of these involve mechanical innovations, although several have depended upon tube or circuit developments.

A. Interchangeable Features

Before the widespread use of the Miller sweep generator, oscilloscopes were generally designed for a more or less limited range of operation, i.e., low frequency, high sensitivity, and slow sweep rate performance, *or* high frequency, low sensitivity, and fast sweep operation. However, the Miller generator made it possible to obtain a total sweep duration that ranged from a fraction of a microsecond to many seconds or minutes. Obviously, the same generator could be used in many different applications.

Consequently, an effort was immediately made to design one instrument to handle many different applications. It was realized that one amplifier, of course, could not be used to greatly amplify fractional-millivolt signals on the one hand, and handle a frequency range of direct current to 10 Mc on the other at the same time. It was recognized, however, that a basic amplifier could be designed to provide a reasonable amplification over this frequency range and that special preamplifiers could then be used to adapt the basic amplifier to the particular frequency and sensitivity needs at hand. These preamplifiers can be designed to "plug-in" to the main instrument. For wide-band use, a further amplification of possibly two might be completely adequate, whereas for narrow-band use, an amplification of several thousand would be available. In this way, a very versatile instrument can be had at a relatively low cost.

This type of design does present a few technical problems. For example, amplifiers in cascade each contribute to a total reduction in bandwidth to less than either individual amplifier.[18] Consequently, each one must have a substantially greater bandwidth than the performance

[18] See Appendix.

intended for the combination. This has required the development of special compensating devices, nonreactive resistors, special amplifier circuits, etc., many of which have been described in previous sections.

While the major use of the "plug-in" feature has been to change the vertical amplifier performance of the oscilloscope, the instrument can just as easily be designed to modify or supplement the x-axis characteristics. Such features as timing marks, delayed sweeps, etc., have been obtained in this way.

B. Multiple-Trace Displays

There are a number of situations where it is desirable to observe more than one aspect of the same signal, for instance, pressure and velocity of a gas or position, velocity, and acceleration of some object. To meet these needs, various multiple-image display devices have been developed. Generally, these are of two types—multiple-beam and multiple-trace devices. In the multiple-beam type, there are actually two or more electron beams with the requisite beam-controlling elements and circuits for each beam. In the multiple-trace type, there is usually only one beam, which is time-shared among two or more signals. Each has its advantages and disadvantages, and which one is applicable depends primarily upon the characteristics of the signal. If the signal occurs only once and its duration is shorter than 10^{-4} sec, the multiple-beam display is the only adequate and satisfactory method to use. For all other signals, the multiple-trace method will usually suffice.

Multiple-trace performance can be obtained by connecting two or more signal channels to the CRT, with a switch to select among them. The various phenomena can then be displayed merely by switching from one channel to the other. Of course, if we include an electronic switch to do the selecting, we can vastly increase the switching rate. There are then various ways of selecting the signal we wish to observe. For instance, the electronic switch can be set to "free-run" or oscillate at some desired rate. In this case each channel is sampled for a discrete length of time, the potential or change of potential during that time is amplified and deflects the beam, and the combined signals of all the channels are presented on the screen. Each signal is presented as a series of line segments, separated by gaps which are filled at different voltage levels with other signals. The proportion of time devoted to one signal will depend upon the number of channels. The number of segments making up the signal image will depend upon the signal duration and the switching rate. It can be seen that for any kind of accuracy, a pulse should contain at least 10 segments, and if it is a complex pulse—more than just a simple trapezoid—then many more than 10 segments would be required.

Using these rather loosely defined criteria, it can be seen that a switching rate of 100 kc, which gives a sampling time of slightly less than 5 μsec in a dual-channel system, will limit the viewing of single complex pulses to durations of longer than approximately 1 msec, or as short as 0.1 msec for a single trapezoidal signal.

One very important mode of operation using an electronic switch is the "alternate-trace" method. If the electronic switch is designed so that it can be triggered from whatever state it is in, the sweep "flyback" transient can be used to initiate the transition. In this way, the sweep is ready to display the next signal on the alternate channel. With this type of operation, the only limitation on the signal character is imposed by the amplifier itself. The signals can occur at random, and thus an arbitrary signal can be compared to a standard timing signal.

As stated previously, for viewing several aspects of single signals shorter than approximately 1 msec, a multiple-beam instrument is necessary. This consists of two complete oscilloscopes with "both" CRTs contained in a single, evacuated envelope. The requirements of each channel will be subject to the same conditions as the single-beam instrument.

Certain simplifications can be made in a CRT which will considerably simplify a multiple-beam instrument. For example, the horizontal deflection plates can be common to all beams, eliminating the need for more than one sweep and horizontal amplifier circuit. However, if it is required that one sweep be progressing at a different rate from the others, the foregoing circumstances will be altered and multiple-beam instruments will be required for even repetitive phenomena.

C. Storage-Type Cathode-Ray Tubes[19]

A new development in CRTs, which offers some new capabilities as well as being a special case of a multiple-trace display, is the storage tube. This permits the placing of several traces on top of one another in sequence (for comparison and recording purposes) as well as the capturing of a single event and immediate study of it. At least one firm is marketing a cathode-ray oscilloscope designed around these tubes, and more are certain to follow. At the present range of operation, their capabilities are limited to relatively slow signals with little detail. The maximum writing rate which can presently be obtained is approximately 1.5 cm/μsec, as compared with about 1000 times this rate with the conventional recording methods. However, there is no reason to assume that these limitations are fundamental.

[19] A sizable literature exists on storage tubes. For an excellent basic book on the subject, which contains a fine bibliography, see Knoll and Kazan (*67*).

VII. Prognosis

As can be seen, even the present state of the art is hard to pinpoint with any accuracy. To make any projection into the future would be rash indeed, since it is nearly impossible to foresee what present work might have some bearing upon future oscilloscope design. Possibly the most obvious trends will be in the direction of high-frequency response, trace storage, and reduction in instrument size.

The CRT designed by Germeshausen *et al.* (*32*) points the way to instruments for displaying phenomena in the submillimicrosecond range. The next few years should see equally substantial advances in this direction. Although forecasting is most dangerous, it seems reasonable to project a response in excess of 10^{10} cps in the not-too-distant future. An additional development that may have some bearing on this situation is the Wamoscope, a microwave display tube announced in the early part of 1957 (*68*).

It also seems reasonable to expect that the storage principle will become relatively common in the next few years. The advantages to the user in the way of ease of comparison, retention of information, etc., are so great that most high-performance, general-purpose oscilloscopes will probably include storage tubes in increasing numbers.

If the transistor can be adapted for general use in the oscilloscope, the physical changes that may result will be very drastic. These devices have been used very little in the oscilloscope, mainly because of temperature limitations, aging characteristics, performance stability, and frequency response. But these limitations do not seem to be inherent. If additional transistor circuits equivalent to existing vacuum-tube circuits can be developed, a great reduction in size could be made. In fact, the CRT would then largely determine the dimensions of the instrument.

The CRT itself is the subject of several attempts toward a reduction in size and a change in configuration. Several organizations are working on "flat" tubes and light intensifiers which would be only an inch or two thick. While the greatest impact of such a development would probably be in the fields of television and radar, it would mean that instrument designers would have much greater freedom in the design of their instruments, and that the form and dimensions of oscilloscopes would not be determined by the CRT, but by considerations of utility and efficiency.

Beyond these rather obvious trends, it becomes more difficult to extrapolate, one reason being, perhaps, that we are tied too closely to the graphical display offered by the oscilloscope. It is difficult to conceive of a display technique which would contain the same easily understood information as the present display, but which does not depend upon a sequential tracing out of the point-by-point development of some phenomenon. Nevertheless, it would seem strange to the *n*th degree if the method developed in 1897 by Professor Thomson to demonstrate that cathode rays were electrified would prove to be the optimum means of displaying transient or fluctuating phenomena.

VIII. Appendix

A. Amplifier Response

1. Relation of Risetime to Bandwidth. "Risetime" as used in this article is defined as the time required for an amplifier to move between the 10 and 90% points in its response to a step function, as depicted in Fig. 24.

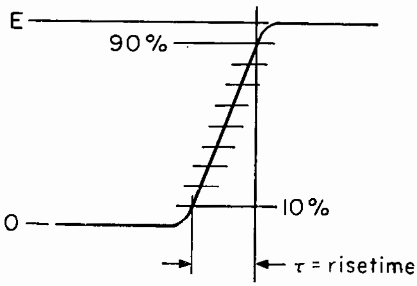


Fig. 24. An all-important concept to the designer of oscilloscope amplifiers. The voltage transition illustrated represents a *loss* of information if the input waveform was a step function. Nevertheless, the observer can compute how much of a loss, whereas if the circuit contained "overshoot," this would represent an *addition* of information which is much more difficult to handle.

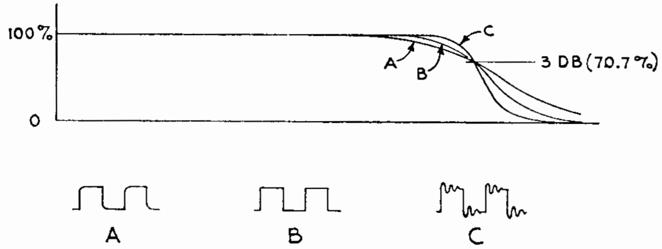


Fig. 25. The relationship between "roll-off" and square-wave response.

"Bandwidth" as used in this article is defined as the frequency range between the two frequencies at which the response of the amplifier is 3 db less (29.3%) than its response at mid-range. In the case of a direct-coupled amplifier, the bandwidth also defines the upper 3-db point (see Fig. 25).

The response of an amplifier (τ, in microseconds) to a step function, in terms of the amplifier bandwidth (β, in megacycles) is related by the following formula:

$$\tau = \frac{0.35 - 0.45}{\beta}$$

or

$$\tau\beta = 0.35 - 0.45$$

The value of the constant is determined by amplifier characteristics and with good design will approach 0.35, with no detectable overshoot on the reproduced pulse (*69*). The shape of the frequency response curve at the upper end—the "roll-off"—determines to a great degree the fidelity of the amplifier response. The situation is illustrated in Fig. 25.

It will be noticed that too shallow a roll-off such as curve A, does not give the reproduced square wave the sharp corners of the original, even though the response does contain much high-frequency energy. On the other hand, too sharp a cutoff will give the result seen in waveform C, which is actually due to the *absence* of certain frequencies, of such amplitude and phase that they would, if present, "straighten out" the top of the waveform (or add to the hollows and substract from the peaks of the oscillation). The best shape for the roll-off to have, for the best reproduction of an arbitrary waveform, has been found to be that of a Gaussian error curve.

2. Testing of Amplifiers for Response. Because of the relations discussed above, it has become something of a standard technique to test the response of amplifiers by their reproduction of a square wave. While it is not possible to make a *precise* measurement of frequency response by use of the square-wave test, it is possible to estimate the 3-db point to within 2 or 3%, which is accurate enough for most purposes.

One of the difficulties of making frequency-response measurements is that it is extremely tedious or nearly impossible to predict what the response of an amplifier will be to an *arbitrary* signal from the frequency response curve. If, however, the circuit will adequately reproduce a square wave of given risetime and fundamental frequency, it will adequately reproduce an arbitrary waveform whose frequency components lie within those same limits. In addition, square-wave testing permits an immediate general analysis of the response and consequently is valuable in determining what may be wrong in the circuit. Oliver (*70*) has written an excellent analysis of this type of testing that is highly recommended.

The development of tubes of the distributed-deflection plate type requires testing techniques that are adequate for the frequency ranges covered. There are many oscillators which cover the UHF region, but as we have seen from our prior discussion, the response of a system to an arbitrary signal is not immediately evident from the frequency response curve. Consequently, square-wave testing techniques were developed to test these UHF CRTs.

Immediately, several problems were evident, two of which were serious:

1. How does one *develop* a step function which will adequately test deflection systems capable of response at 3000 Mc and beyond?

2. How does one *know* that the step function is distortionless?

Taking them separately, the best way to develop a dependable, extremely rapid step function (≈ 0.1 mμsec or 10^{-10} sec risetime) is by the opening and closing of a mechanical switch. To avoid contact bounce and to provide for the initial high surge of current, switches are used which have mercury-wetted contacts. Risetimes of 0.12 mμsec are obtained at signal levels which are sufficient to get a good readable deflection on the tube. In this way, the performance of the deflection system can be analyzed to 3000 Mc and beyond.

The second question is a little more difficult to solve. The reason for developing the switch in the first place was to test the high-frequency CRT. To test the switch, we presumably have to have a CRT whose characteristics exceed those of the switch.

C. H. Moulton (unpublished) solved this problem by essentially piercing a piece of coaxial line so that a beam of electrons can be passed immediately adjacent to the center conductor. A signal passing down the line will then deflect the beam according to the strength and polarity of the signal. Because of the dimensions of the elements involved, the frequency of response is very high- about 4000 Mc—and with properly terminated fittings, the uniformity of response is apparently very good (see Fig. 26).

One of the acute problems encountered in the design of this device concerned the vacuum seal required at each end of the coaxial deflection system. The change in impedance from air dielectric to most materials used for vacuum seals is so abrupt that severe reflections will result if a fast pulse is passed down the line. This effect is not so noticeable if one is concerned with observing continuous waves, since it is usually evident only as a change in the slope of frequency response curve. To a fast pulse, however, the circuit may ring, causing spurious responses on the observed signal. This problem has not yet been satisfactorily solved. It is indicative, however, of some of the situations that must be met whose solution does not depend upon the design of the beam-deflection elements.

3. Cascading of Amplifiers. As indicated in the text, if a certain bandwidth is required from a group of cascaded amplifiers, the bandwidths of the individual amplifiers must be much greater. The situation can be illustrated easily.

Assume that an amplifier is 3 db down (or has 70.7% the mid-range response) at 1 Mc. If we cascade an identical amplifier with this one, we will find that the response at 1 Mc is now 70.7% of 70.7%, or 50%

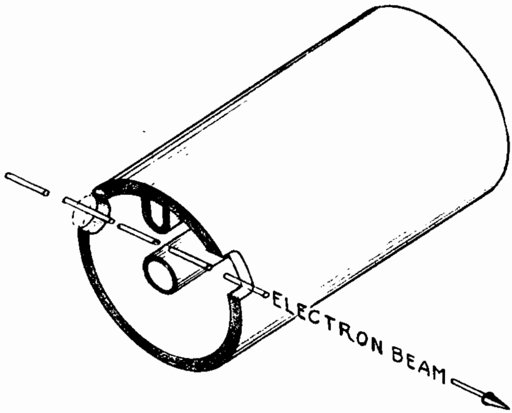


FIG. 26. A low-sensitivity short-risetime deflection system for observing fast transients. Risetimes as short as 0.12 μsec (1.2×10^{-10} sec) have been observed with this device.

(6 db down in response). The 3-db point is obviously less than 1 Mc. We find, in fact, that the bandwidth β_t of two or more cascaded amplifiers is

$$\beta_t = \frac{1}{\sqrt{(1/\beta_1)^2 + (1/\beta_2)^2 + \cdots}}$$

The equation is a little neater when it deals with the *risetime* of several cascaded amplifiers:

$$\tau_t = \sqrt{(\tau_1)^2 + (\tau_2)^2 + \cdots}$$

This same equation will give the observed risetime of a pulse of any given rise time after passing through a system with a known risetime.

Consequently, referring to the previous discussion of the fast pulse generator and the special deflection system to observe it, we can make some valid assumptions regarding these two devices. A pulse from the pulser, when sent through the deflection system, has an observed risetime of 0.12 mμsec. We can then infer that the risetime of each will be less than this value; in fact, they can both be as short as 0.085 mμsec, or one can be even shorter with the other being correspondingly longer.

B. Use of Cathode Followers

One outstanding feature of many of the newer circuits has been the copious use of cathode followers. Although the cathode-follower has long been used for driving difficult loads, such as cables, motors, signal output terminals, etc., the latest uses reveal a widening conception of the circuit. The highly simplified circuit in Fig. 27a will help to illustrate this point. Of seven tubes shown, only one is *not* a cathode follower.

1. Low-Capacitance Load. This use borders on the classical, impedance-matching use of the cathode follower, but nevertheless is seldom seen. In this role it is found as a coupling device between the two tubes of a multivibrator, between stages of an amplifier, between plate and feed-back capacitor of a Miller sweep generator, etc. Tubes *B* and *G* are examples of this type of use. The prominent advantage here is that the driving circuit (which is usually a high-impedance plate circuit) sees only the very small input capacitance of the cathode-follower grid. An additional important feature is that the input to the succeeding stage or element is characterized by the low impedance output of the cathode-follower.

Examining tube *B*, we see that the only capacitive load on the plate of the Miller sweep generator tube *A* is the input to tube *B* and the small stray capacitance associated with the load resistor. The low impedance of the cathode circuit of tube *B* minimizes the effect of the stray capacitance of the wiring, which would otherwise seriously compromise the function of the timing capacitor *C*. Tube *G* also illustrates both these features, except that it is used to drive a deflection plate of a CRT, which is a very high impedance load.

2. Functional Isolation. Many functions required in a device will cause changes in impedance, average operating level, etc., which can have a detrimental effect upon the desired operation. Examples are combining positioning voltages with signals, introducing a waveform with one d-c level into a circuit operating at other levels, etc. These examples are illustrated in the circuit under discussion by tubes *C* and *D*, and tube *E*.

Tube *C* introduces the positioning voltage by varying the d-c level of the grid of tube *B*. The impedance of the circuit varies only a small fraction of a per cent of the total impedance, consequently introducing practically no distortion of the sawtooth waveform even though it changes in d-c level by nearly 100 volts.

The cathode circuit of tube *D* contains the attenuator that controls the feedback between tube *G* and tube *E* for the magnifier operation. Tube *E* introduces the sweep waveform, whether normal, magnified, or

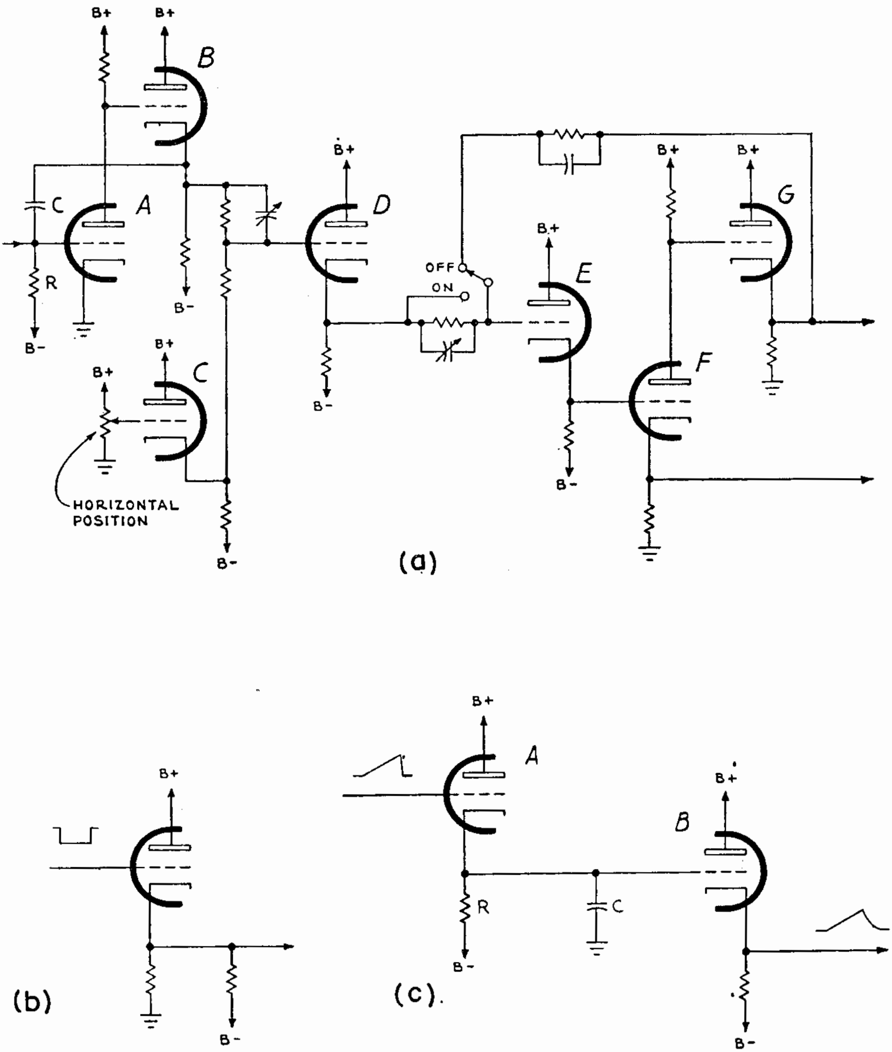


FIG. 27. Simplified actual circuits using cathode followers in various ways. (a) A sweep amplifier circuit. (b) Cathode follower used as a switch at clamp tube. (c) Hold-off circuit.

positioned, into tube F. It will be seen that large variations in signal amplitude and d-c level appear at the grid of tube F. Consequently, there may be "cutoff" or "saturation" conditions existing at some parts of the sweep waveform. However, the d-c nature of the circuit insures that these distorted portions of the waveform *always* lie off the visible portion of the CRT screen, so that they can never affect the accuracy of presentation. In other words, the portion of the waveform we are interested in observing, whether magnified, positioned, or normal, never occurs in a nonlinear operating region of any circuit.

Tube *F* is a dual-purpose stage, one portion operating as an amplifier and the other portion operating as a cathode-follower. The cathode-follower portion drives the cathode of a grounded-grid phase-inverter whose plate, like the plate of tube *F*, drives the grid of a cathode-follower which is the deflection stage.

There are other isolation uses than those illustrated in this sweep amplifier circuit. For instance, the grid of the cathode-follower circuit in Fig. 27b acts simply as a switch, with the cathode free to behave at the dictates of the following circuit. In this particular case, this circuit is used to initiate the operating cycle of the Miller sawtooth generator, and the grid remains relatively fixed when cathode current ceases to flow in the cathode follower.

An additional isolation use for cathode-follower circuits is illustrated by Fig. 27c. This circuit is used to introduce the time-delay that constitutes the hold-off portion of the cycle discussed earlier. It can be seen that while the grid of tube *B* will closely follow the grid of tube *A*, on the positive-going excursion of the sawtooth, the negative-going portion will be determined by the values of *R* and *C*. The signal on the cathode of tube *B* can be applied directly to the grid of the sweep-generator-controlling multivibrator, or it can be mixed with other signals to perform gating functions, etc.

In any case, the cathode followers serve to isolate the driving circuits from any activity that might take place in the driven circuits that changes the signal. Consequently, it will be found that most modern high-performance sweep generators use copious quantities of cathode-follower circuits. The increase in performance nearly always outweights the increase in complexity involved.

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With such a subject as dealt with in this paper, it would be impossible to cover the field completely. As we progress from basic research to applied research to technology, the publication of papers expands enormously and then falls off rapidly, particularly as we begin to examine the techniques of individual firms. Consequently, we find few specific references to the circuits used in commercial devices, although there are many concerning the individual elements comprising the complete circuits.

There are certain publications which can be cited, not only for the work which they describe, but their own bibliographies.

For example, the article by J. T. McGregor-Morris and R. Mines (*3*) is possibly the most exhaustive survey of this subject in existence. Anyone who is interested in the first few decades of oscilloscope history would be well advised to look it up in his local technical library.

Similarly, S. Ramo and H. P. Kuehni's (*4*) article has an excellent bibliography of work subsequent to McGregor-Morris and Mines. Also, it lists a great deal of the early design and use of the oscilloscope in the electric power industry. J. Czech's (*5*) book refers to much of the work done in Europe and would be most valuable to Americans interested in this field.

O. S. Puckle (*7*) has written possibly the most comprehensive survey of timebases in existence, and is a most excellent source book. Quite a bit of system development has taken place since the publication of the Second Edition, but most of the circuit elements presently used are described by him.

Of course, the Radiation Laboratory Series is one of the monumental compiling and publishing efforts of the time and comprises an invaluable reference library for almost any circuit engineer. Again, much of the material is old, but few basic circuits are missing.

For a more detailed treatment of any particular subject, the references and their bibliographies should be consulted. The author will be happy to enlarge on any particular point by personal communication.

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