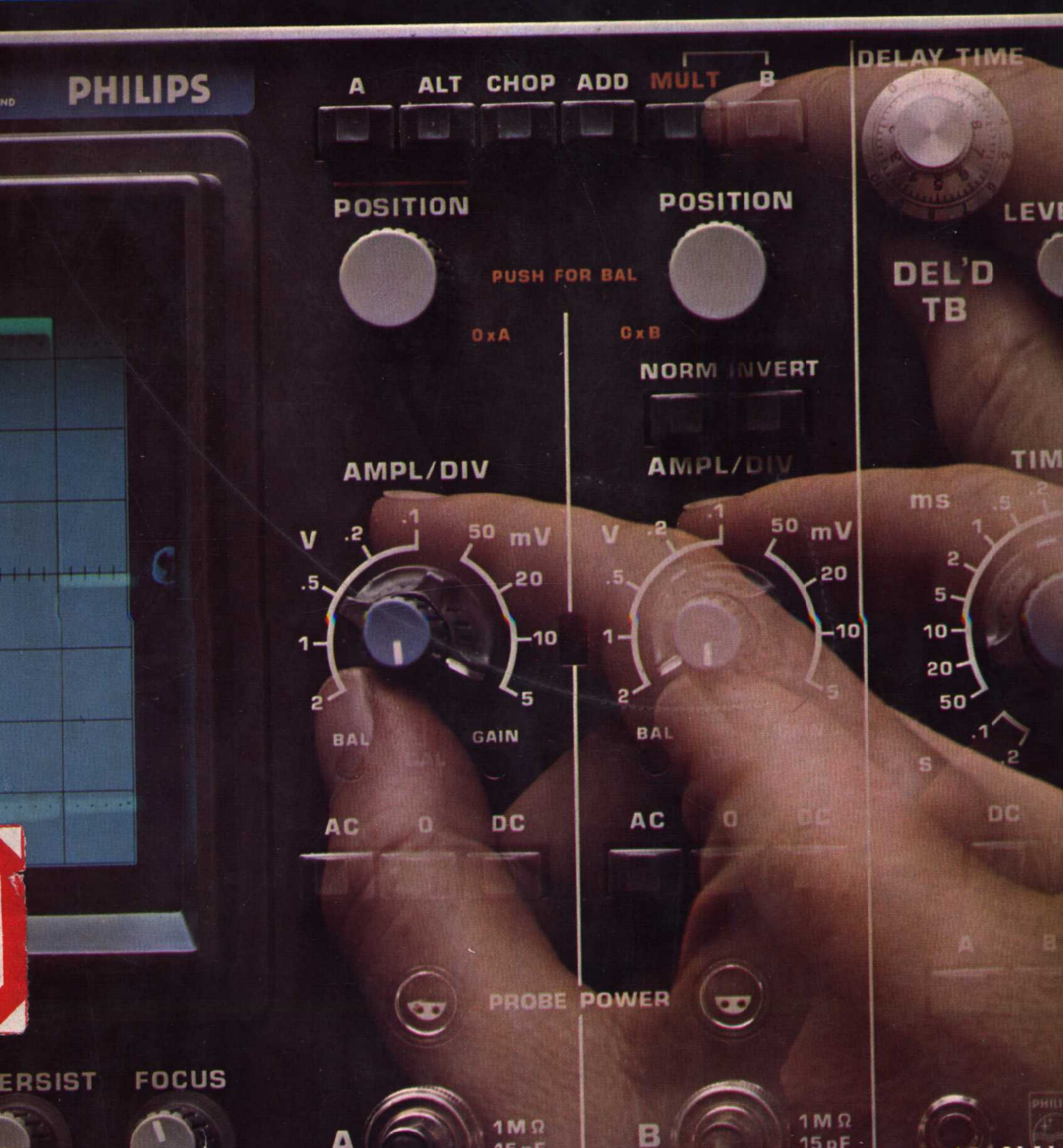
OSCILLOSCOPES

Functional Operation and Measuring Examples

Rien van Erk



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Philips Test and Measuring Instruments,
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PREFACE

Modern oscilloscopes are finding use not only in the traditional electrical and electronic measuring areas but also in a wider number of fields, including applications where purely mechanical methods were used before. Apart from developing facilities to make modern oscilloscopes simpler and more straightforward to use, much effort has gone into keeping these instruments up to date with technology—from exploiting the latest large-scale integrated (LSI) circuitry for extra reliability to providing facilities to match the latest high-speed circuit elements.

Making the best use of any facility requires an understanding of the basic elements and how to apply them successfully. With the oscilloscope becoming rapidly established as almost the standard test and measuring instrument, the need to understand and get the best results out of it becomes paramount.

This book not only attempts to help the specialist electrical engineer make the most of the oscilloscope but also provides a solid basic understanding for the nonspecialist, such as the mechanical engineer discovering the advantages of combining electrical measurements with mechanical methods. Students will also get a basic understanding of oscilloscope operation.

Many books and booklets have already been written on the subject of oscilloscopes, but most of these either describe the electronic-circuit building blocks or are a collection of experiments with mainly electronic phenomena. This book is designed to emphasize the use of the oscilloscope to allow the best use of its various facilities.

Starting with a discussion of the basic functions of an oscilloscope, and particularly the cathode-ray tube, the various extra facilities available for operator convenience are quickly introduced. Special designs are required for some applications—such as storage and sampling—and these are explained in more detail. Probes form an essential link between the oscilloscope and the device under test. Therefore, a separate chapter on these is fully justified. This chapter finishes the section of the book on the basics of oscilloscopes.

Basics are pointless in isolation, so measurement pitfalls are explained in order to give the reader guidance in minimizing measurement mistakes. And to wrap up the subject, a whole series of exercises are provided showing how the oscilloscope can be exploited to the limits of its capabilities to provide maximum accuracy and resolution. Of necessity, these are mainly electrical applications and sufficient detail is provided to make them easily repeatable in the classroom.

Understanding the specifications of oscilloscopes is important for anyone contemplating buying such an instrument and this subject is dealt with by detailed explanations of the specifications of a simple oscilloscope and a sophisticated oscilloscope in Chapter 7.

A further aid to the nonspecialist and specialist alike is a glossary of over 200 terms and the tables of SI electrical units.

ACKNOWLEDGMENTS

Many contributions are necessary to complete a book such as this one and much information has been taken from existing publications of the Philips' house. One such publication is Joop Aartsen's book "Zeroing in on ones and zeros," which was used as a basis for Chapter 2.

Very valuable were the discussions with, and the willing assistance, of my laboratory staff and in particular the contribution of Toon Kluytmans, who patiently executed all test setups for the measuring examples.

Last, but by no means least, special credit must be given to Frank Bregman, who conscientiously read the draft and gave many valuable suggestions for improvements, so that this book could be completed in its present form, and to Paul McCallum who carried out the final reading.

RIEN VAN ERK

CONTENTS

1

BASIC OPERATION OF THE OSCILLOSCOPE

1.1 WHY VISUALIZATION OF THE SIGNAL?

The specific characteristics of a signal can be measured by a variety of instruments. For example, a counter can measure a signal's frequency or its period, and an ac voltmeter can measure the rms value of the signal. Although these instruments are very useful and can be more accurate than the oscilloscope, their application is mainly limited to the measurement of one parameter of the signal. With an oscilloscope one can visualize the signal of interest and also observe whether the signal contains properties that would not be made apparent by most other instruments (for example, whether the signal is superimposed on a dc level, or whether there are noise or relative hf oscillations present with the signal at the test point). Thus the oscilloscope is a more valuable instrument because it gives an exact visual representation of the signal waveform.

Figure 1.1 shows a chart recorder drawing a graph of a signal as a function of time. Of course, the recorder can only create a replica of the signal if the pen follows the excursions of the signal exactly, and if the paper moves at a constant speed. The oscilloscope works in a similar way: The spot follows the excursions of the signal in the vertical direction and at the same time the spot is moved in the horizontal direction at a constant speed. The graph on the recorder is distorted when the paper speed does not remain constant. In the same way, the display on the oscilloscope is distorted when the ramp voltage—a voltage that increases linearly with time—is not perfectly linear. At this point, the similarity between the recorder and the oscilloscope ceases.

The recorder will draw a graph as long as paper is being transported along the pen system. In the oscilloscope we have one screen on which a part of the signal is written during a certain time span. In order to obtain a stable picture, the oscilloscope will draw a great many of those parts of the signal, one part after the other and each one covering the previous one exactly. Thus the eye observes one steady picture of the waveform. It is assumed here that the signal is repetitive in time. The method of obtaining a steady picture is discussed later in this chapter.

There is a much bigger distinction between the chart recorder and

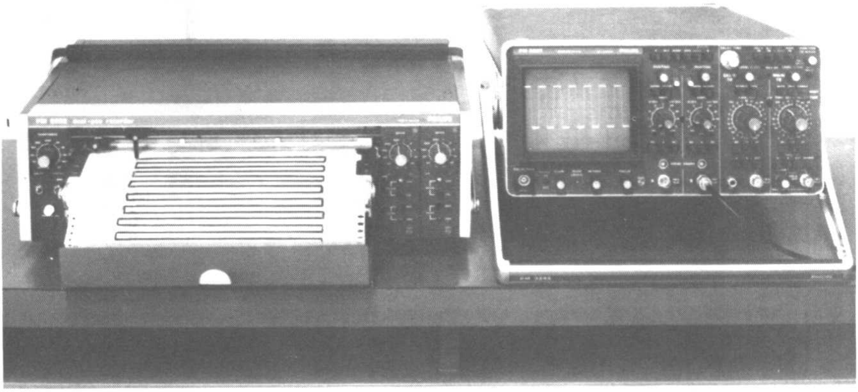


Fig. 1.1 To create an exact replica of a time-variable signal, the recorder paper speed must be constant and the oscilloscope sweep time must be linear.

the oscilloscope, however. The writing system of the recorder has a certain mass, whereas the picture on the oscilloscope screen is written with a beam of electrons that are virtually massless. Therefore, the speed of the recorder system is limited to a few transients per second, while the electron beam can visualize transients in the nanosecond (10^{-9} second) area. The oscilloscope is thus able to visualize much faster phenomena than the recorder, and it is primarily for this reason that the oscilloscope is as widely used as it is today.

1.2 THE CATHODE-RAY TUBE

The heart of the oscilloscope is the cathode-ray tube, since it performs the basic functions to convert a signal into an image; it is the output device, or display portion, of the instrument. The cathode-ray tube (CRT) is a vacuum tube similar in shape to a TV picture tube, as illustrated in Fig. 1.2. The assembly of electrodes in the narrow part of the tube is known as the *electron gun*. The electron gun furnishes a controllable source of electrons and focuses these electrons into a beam with the focus point (spot) on the screen. The beam is deflected vertically and horizontally in the deflection section before striking the layer of phosphor at the screen to produce light. The operation of the CRT can best be studied by dividing the tube into sections, referring to Fig. 1.2 and discussing each section in turn.

The Electron Gun

In the electron gun the electrons are generated by heating the cathode K, which then emits the electrons. These electrons are shaped into a beam in the gun. The intensity of the beam is controlled by the voltage between the cathode K and the Wehnelt cylinder G. If this voltage is such that no electrons arrive at the screen, the condition of the tube is called *blanked.* The electrons emitted by the cathode are brought to a first focus by means of an electrostatic field produced between the Wehnelt cylinder G and anode a_1. From this first focus, or crossover point, the beam begins to diverge until it enters a second electrostatic field between anodes a_1 and a_3 and anode a_2. Anode a_2 is the main focus electrode; by varying the potential at this point, the beam can be brought to a sharp spot on the CRT screen. Acceleration of the electrons from the cathode towards the screen is caused by the electrostatic field existing along the axis of the tube. This field is established by the difference in potential between the cathode and the interconnected electrodes a_1 and a_3, usually about 2 kV.

Deflection Sensitivity

Located between the electron gun and the screen are two pairs of *deflection plates.* These plates are so arranged that the electrical fields between each pair of plates are mutually at right angles. Under the influence of the electrical field produced between each pair of plates, the electron beam is deflected towards the plate which is at the positive potential with respect to the other. Since the same applies for the other pair of plates, it is possible to deflect the beam in two directions, that is, the *X* and *Y* coordinates of the screen. In normal operation the *X* deflection is generated

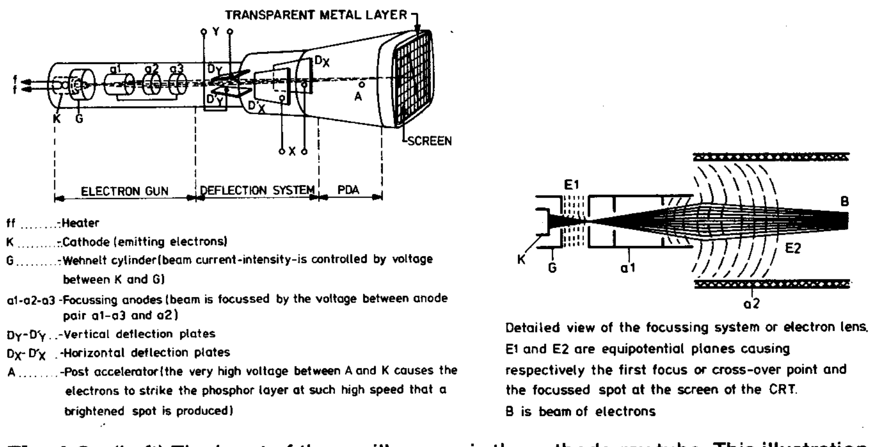
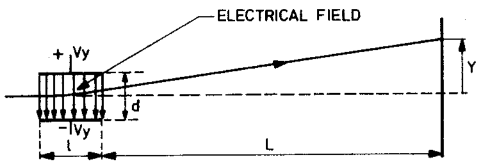


Fig. 1.2 (Left) The heart of the oscilloscope is the cathode-ray tube. This illustration shows the tube construction and identifies the essential parts. (Right) Detailed view of the focusing system or electron lens. E_1 and E_2 are equipotential planes causing the first focus or crossover point, and the focused spot at the screen of the CRT. *B* is the electron beam.

Fig. 1.3a The electrical field causes the electrons to be deflected towards the positively charged plate.



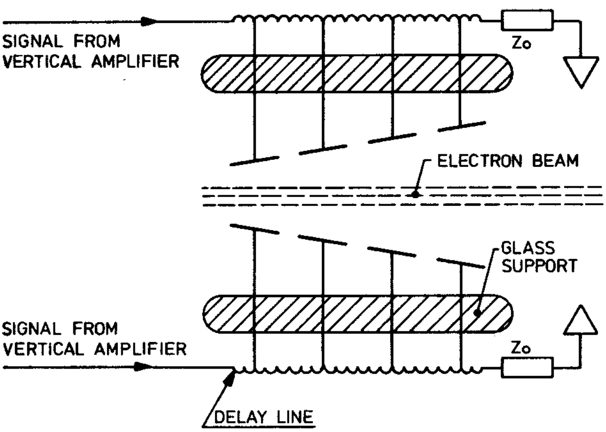


Fig. 1.3b Segmented deflection plates increase the bandwidth of CRTs.

within the instrument in the form of a repetitive left-to-right sweep across the screen, while the signal to be measured produces the *Y* deflection.

The deflection sensitivity (DS) establishes the number of centimeters of deflection on the screen per volt of deflection voltage between the plates. Referring to Figs. 1.2 and 1.3*A*, it can be derived that

$$DS = \frac{Y}{V_y} = \frac{l \cdot L}{2 \cdot d \cdot V_z} \quad \text{cm/V}$$

In this expression, V_z is the difference in potential which the electrons pass from the cathode through the electron gun as far as the deflection plates (for example, $V_z = 2$ kV).

Segmented Deflection Plates

In high-frequency oscilloscopes the vertical deflection plates may be segmented (see Fig. 1.3*B*). The object of this type of CRT is explained in the following paragraphs.

With normal deflection plates the electrons of the beam may remain so long between the plates that high-frequency signal transitions occur during the time the electrons travel along the deflection path. The effect on the deflection of the beam would then be less than the input signal requires, or less than on low-frequency signals.

By segmenting the deflection plates, a specific drive per deflection segment may be obtained, resulting in a proper deflection of high-frequency signals. In this case the stray capacitances between the plates are used to form a delay line together with the externally connected coils. The delay line is terminated by its characteristic impedance Z_0. In this way the propagation of the electrical signal through the delay line toward the termination takes somewhat more time.

By matching the propagation velocity in the delay line to the velocity of the electron beam between the plates, each electron is forced by the same phase of the signal at each segment, resulting in a constant deflection sensitivity of all frequencies within the CRT's (increased) bandwidth.

The PDA System

Referring to Fig. 1.2, the next section towards the screen is the *postacceleration area.* Not every tube in use today has acceleration. This depends on the highest sweep frequencies to be supplied to the tube; for the tube this means the highest writing speed to be displayed. For time coefficients up to 0.1 μs/div no postacceleration is needed. Thus, 10-MHz sine waves are displayed with 1 period per division. In this case the inside of the tube from the deflection plates to almost as far as the screen is covered with a conductive coating of Aquadag. The Aquadag coating is connected to anodes a_1 and a_3 at 0-V potential. This kind of tube is called a *monoaccelerator tube,* because after the electrons pass anode a_3 no acceleration forces are applied to them. In order to raise the writing speed, anodes a_1 and a_3 in the monoaccelerator can be brought to a potential of approximately 4 kV. But as can be seen from the relation of the deflection sensitivity (DS), it follows that increasing V_z from 2 to 4 kV causes the DS to decrease proportionally.

In order to overcome the problem of the writing speed, postdeflection acceleration (PDA) is applied. This method allows the focusing and deflection sections to be operated at even lower voltages than the monoaccelerator tube. These lower operating voltages reduce the velocity of the beam in the deflection system and are an aid to better deflection sensitivity. After the beam has been deflected, it is then accelerated in the postacceleration area to give a high light output.

However, there are some disadvantages with postacceleration, which can be better understood if we consider the successive developments that have taken place in the past decade.

First, instead of the Aquadag coating used in the monoaccelerator, a continuous electron lens over the entire funnel of the tube is constructed

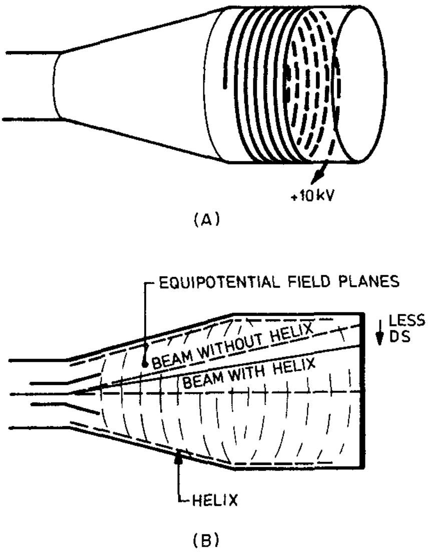


Fig. 1.4 (*A*) The helically-wound resistive material used for the post-deflection acceleration system. (*B*) The influence of the helix on the deflection sensitivity (DS).

from resistive material that is helically wound (Fig. 1.4*A*). The applied acceleration voltage is about 10 kV with respect to the cathode. A disadvantage of this system is that the electrical field is converging, thus moving the electrons towards the center of the screen. Thus the light output was improved at the expense of the deflection sensitivity (Fig. 1.4*B*). This type of CRT is seldom used today.

The compression of the helix PDA tube can be eliminated by a mesh located in the CRT just beyond the deflection plates. Now the converging field can even be transferred into a diverging one, using a continuous conductive layer similar to Aquadag for PDA. However, the mesh is a metal electrode, and as a result of the voltage applied to it (see Fig. 1.5) will intercept 30 to 50% of the beam electrons, thereby again reducing the light output. Another disadvantage of the mesh tube is that the spot size is increased, compared to the helix PDA tube. The helix field is

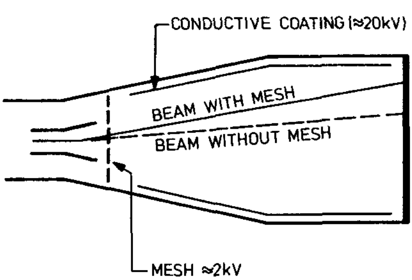


Fig. 1.5 A mesh placed into the helix increases the deflection sensitivity.

converging, which reduces the DS; but also, the beam is compressed and consequently the spot size is reduced.

To overcome the problems of the mesh tube, but mainly the problem of reduced light output, the PDA voltage has been increased to about 20 kV, which also compresses the beam somewhat, resulting in a slightly smaller spot size again. To further increase the deflection sensitivity, the helix has become domed (see Fig. 1.6). The gain in DS is even such that the CRT can be shortened and still retain an acceptable DS. Shortening the CRT is an important factor in reducing the overall size of an instrument. An equally important factor in reducing the size of an instrument is the application of integrated circuits.

The Screen

The last section illustrated in Fig. 1.2 is the *screen*. The beam of electrons, brought to a focus at the screen, is invisible. The screen is coated internally with phosphor, which emits light on the spot where the electron beam hits it. The color of the radiation and the duration of the "afterglow" depend on the type of phosphor used. After the phosphor layer is applied to the screen, a very thin metal layer may be vaporized over the phosphor (Fig. 1.2). This metal layer is transparent to the electron beam and acts as a heat sink for the heat developed in the generation of light in the phosphor. Without this transparent metal layer the phosphor could be burned away by the high energy of the electron beam, after which no radiation of light would be possible. Another very important advantage of the metal layer is that the light is reflected to a certain extent, resulting in a higher light output on the screen.

In order to take measurements by means of the screen, a graticule has to be placed in front of it. This *external graticule* gives rise to parallax in the readout because it is not in the same plane as the phosphor. However, the external graticule can easily be removed for other types of measurements, for example, *X-Y* measurements.

To overcome the problem of parallax, *internal graticules* may be pro-

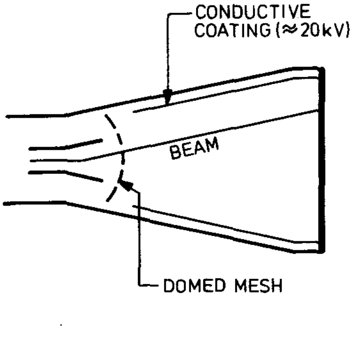


Fig. 1.6 The use of a domed mesh permits the CRT to be made shorter in length while maintaining the increase in deflection sensitivity.