chapter 7
OUTPUT EQUIPMENT

7.1 General Remarks

Since the solution of a problem on a repetitive differential analyzer becomes available immediately and is repeated a number of times per second, the cathode-ray oscilloscope represents the most natural display device. This represents one of the chief advantages of the repetitive computer over one-shot analog computers. Particularly in problems involving the optimization by parameter adjustments, the fact that the effect of a parameter adjustment becomes visible at once greatly simplifies the solution procedure. Photographs of the tube screen provide permanent records of the solution.

The chief difficulty with oscilloscopic displays is that high accuracies are difficult to obtain without the use of auxiliary equipment. Inaccuracies arise from two basic causes:

1. The relation between beam deflection and deflection voltage is generally a nonlinear one. This nonlinearity is particularly pronounced for large beam deflections both in the horizontal and vertical directions. It therefore becomes necessary to apply a correction factor depending upon the coordinates of each point of the solution.
2. The oscilloscope trace generally has an appreciable width, making precise measurements difficult.

Accuracy limitations of oscilloscopic equipment were for many years the limiting factor on the over-all accuracy of repetitive computers and were in some measure responsible for their delayed acceptance. In recent years several manufacturers have developed high precision electronic devices that greatly increase the accuracy of oscilloscopic measurements. A description of one of these is given in some detail in Section 7.2.

For more precise measurements an output system displaying the instantaneous values of the solution voltages at a selected point in the repetitive cycle is very useful. Such a system, which lends itself to digital as well as analog read-out, is described in Section 7.3. The use of a special time-base marker facilitates the accurate calibration of the horizontal (time) axis of oscilloscopic displays. The description of a novel method for employing low-speed output devices for the display of a high-speed solution concludes the chapter.

7.2 Oscilloscopic Displays

George A. Philbrick Researches, Inc. has developed an "electronic graph paper" to provide a convenient and accurate calibration of the entire cathode-ray tube screen. The display system will display simultaneously up to 8 input variables on a rectangular-coordinate grid. All input signals are sampled for display at virtually the same moment, so that their waveforms are seen in their correct time relationship. This sampling occurs at every 62.5 μsec for each of the input signals followed by immediate conversion to corresponding points on the coordinate system. These points are so closely spaced that they appear as a single clear line. A clearly defined coordinate system is displayed full-scale over the entire face of the 17 inch cathode-ray tube at the same time. The horizontal lines indicate voltage, the vertical lines time, both displayed with precision. At a glance, the absolute amplitude and time position of each of the signals can be determined precisely. Because input signal waveforms and the lines of the coordinate system are scanned together and simultaneously by the same vertical sweep, errors stemming from nonlinearity, parallax, and drift are obviated. Any changes affecting signal waveforms will also distort the coordinate lines to exactly the same degree, eliminating the relative error. The heart of the display system is a precision 16 kc crystal oscillator. The frequency of this "clock" is maintained constant to within 0.01%. All the circuits involved in time measurements use triggering pulses derived from this clock. The scanning of the cathode-ray tube is accomplished by a vertical flying-scan system in which the scanning voltage flies from −100 to +100 volts at each clock pulse. The high-speed scanning voltage is constantly compared in a coincidence circuit with each of the input signal voltages. Whenever a coincidence occurs a very short brightening pulse is delivered to the cathode-ray tube. Thus a single bright spot occurs on the screen for each signal input every time the high-speed scan passes by it.

To produce the twenty-one horizontal coordinate lines, twenty-one precise reference voltages are introduced to coincidence circuits in exactly the same manner as the eight signal input voltages. Again brightening pulses to the cathode-ray tube produce the spots forming the horizontal lines. The 101 vertical lines are produced by voltage stages applied to the cathode-ray tube grid at precise divisions of the display interval. These voltages stem from the same binary counters that trigger the horizontal sweep voltages. Pulses for the binary counters come directly from the crystal oscillator. To facilitate interpretation every fifth line is intensified. The time required to produce a single display frame by one complete sweep of the face of the cathode-ray tube can be set to 25, 50, 100, 211, 500 msec and 1, 2, 5, 10, 20, and 50 sec. In this way the unit is suitable for slow- as well as high-speed operation. Auxiliary camera units are available to obtain a permanent record of the complete solution.

In Figure 7.1*a* eight solutions are displayed simultaneously. These are the step responses of eight cascaded first-order lags. In Figure 7.1*b* the results of system optimizations in a pneumatic engine control problem is shown. The upper curve biased to +50 volts, indicates flapper valve displacement, the error-sensing device behaving as an undamped spring-mass system. The middle curve indicates pneumatic actuator position. The lower curve biased to −50 volts indicates engine output sensed as pressure. All curves indicate response to a step change in engine pressure.

An alternative method for obtaining high accuracy and precision with oscilloscopic displays is to employ an externally calibrated reference voltage line projected on the screen at the same time as the solution. By varying the reference voltage this line can be moved up and down the oscilloscope screen until it coincides or is tangent to the solution curve in the region of interest. Since this reference line is subject to the same distorting influences as the signal, the magnitude of the reference voltage at the measuring position will be identical to the signal ordinate.

7.3 Measurement of Instantaneous Values

To circumvent the difficulties attending direct measurements on the face of an oscilloscope, separate circuits have been developed to permit the determination of the solution at specific instants of time along the repetitive operating cycle. A schematic diagram of such a system is shown in Figure 7.2. An integrator is employed to produce a sawtooth-voltage wave of the same frequency as the repetition rate of the analyzer. The integrator output is compared with the output voltage of potentiometer P_1 by amplitude comparator A. The output of this comparator will then be a voltage pulse that occurs at a time after the start of the computer cycle, which is determined by the setting of potentiometer P_1. The combination of the integrator, comparator A, and potentiometer P_1 therefore constitutes a linear time-delay circuit. The output of this delay circuit becomes an input to the coincidence detector.

Amplitude comparator B compares the transient voltage $f(t)$ comprising

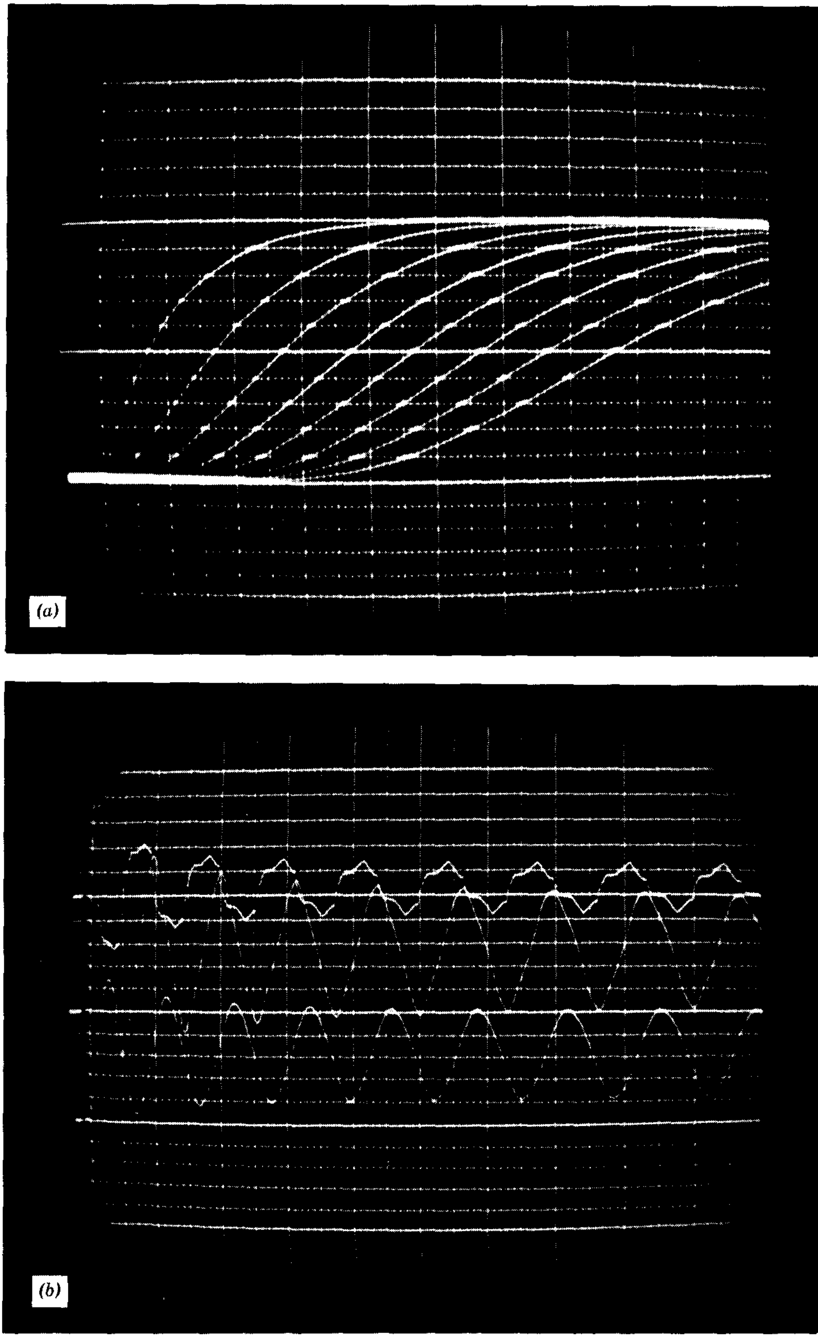

Fig. 7.1 (*a*) Simultaneous display of eight solutions (George A. Philbrick Researches, Inc.). (*b*) Display of system optimization problem (George A. Philbrick Researches, Inc.).

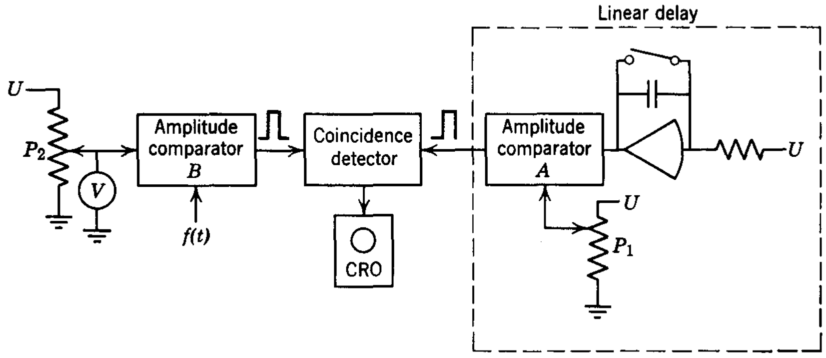

Fig. 7.2 Measurement of instantaneous voltage values using coincidence detector.

the computer solution with the output of potentiometer P_2. When the two inputs are equal, this comparator applies a pulse to the other input of the coincidence circuit. Potentiometer P_2 is adjusted until the desired coincidence is obtained. The voltage output of P_2 as measured by a voltmeter with a high input impedance then constitutes the solution. A cathode-ray oscilloscope can be employed to detect the coincidence signals.

Figure 7.3 illustrates a modification of the measuring system which is particularly suitable for rapid measurements. Rather than seeking a point of coincidence, the value to be measured is read directly on the voltmeter. The output of the amplitude comparator A in Figure 7.2 rather than being applied to a coincidence circuit serves to close an electronic switch. The charge time of capacitor C does not present any problem, since the same solution of the differential equation is repeated a great many times. The forward resistance of the electronic switch is therefore not critical.

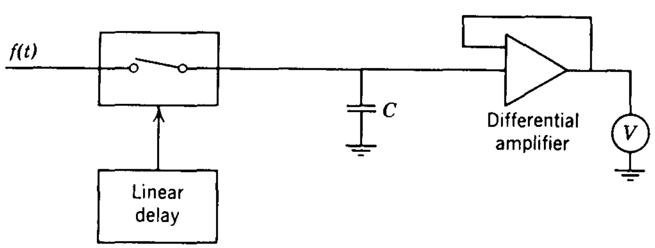

Fig. 7.3 Measurement of instantaneous values of voltage without coincidence circuit.

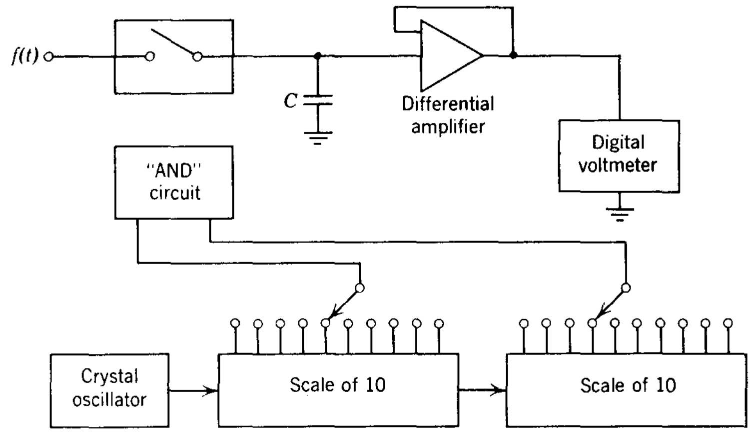

Fig. 7.4 Digital measurement of instantaneous values.

In view of the over-all accuracy of repetitive differential analyzer solutions, measurements at 100, or at the most 1000, equidistant sampling points are generally sufficient. To this end, the circuit in Figure 7.3 can be modified to permit digital measurement of these values. A block diagram of a device for measuring at 100 sampling intervals is shown in Figure 7.4. This permits rapid and precise recording of results. A stable crystal oscillator is included in the instrument to serve as reference for accurate absolute measurements of integrator time constants.

Aleksic[1] has considered in detail the operation and the error analysis of output systems of this type, and Perotto[2] has described a commercial realization. Accuracies of $\pm 0.5\%$ of a maximum ± 100 volt-range are readily obtained. Verification of the accuracy of the amplitude measurements is very simple. It is only necessary to place at the input a constant voltage and to check with a voltmeter if the reading at the input and the

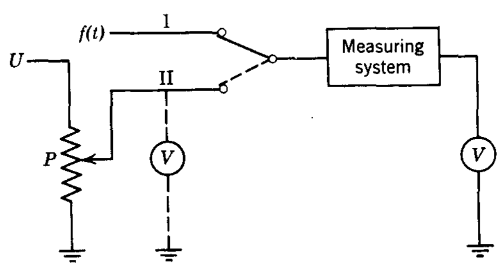

Fig. 7.5 Elimination of the effect of errors in the measuring system.

output of the system is identical. It is interesting to note that one can in this way with little difficulty eliminate completely all errors introduced by this system of measurement. For this purpose the measurement is effected in two steps as shown in Figure 7.5. First, $f(t)$ is measured, and the voltmeter reading is recorded. In the second step a constant voltage is applied to the input. With the aid of potentiometer P the d-c input voltage is adjusted until the voltmeter gives the same reading as in step 1. The voltage indicated by the adjustment dial of potentiometer P is then equal to $f(t)$.

7.4 Time-Base Calibration

In order to attain a maximum of accuracy it is expedient to complement the preceding measuring system with a pulse generator to provide an accurate calibration of the independent variable. Numerous types of timing devices have been developed in the past. One circuit due to Rideout[3] that has been found useful in repetitive differential analyzer applications is shown in Figure 7.6. The impulse frequency is 1250 cycles/sec. The heart of this unit is a stable source of frequency. Since great precisions are not required, a quartz oscillator is not necessary. The oscillator is synchronized with the rectangular voltage wave which controls the operation of the repetitive differential analyzer. The output of the oscillator can be readily applied to the control grid of the cathode-ray oscilloscope which serves to display the solution of the equation.

7.5 Use of Low-Speed Output Devices

Although high-speed display devices such as the cathode-ray oscilloscope are the natural output instruments for repetitive differential analyzers it is possible to obtain satisfactory plots of solutions using devices having much more limited bandwidths, such as servo-driven two-coordinate plotters. Blake[4] has described a method for effecting the necessary frequency transformation. This method does not constitute a change in the scale factor; rather during each repetitive cycle only one solution point is recorded. By making the time interval between the sampling intervals differ from the period T of the solution by a small factor τ the whole solution will be recorded after n repetitive cycles, where $n = T/\tau$. This is illustrated in Figure 7.7.

For example, if

$$T = 0.01 \text{ sec}$$
$$\tau = 10^{-5} \text{ sec}$$
$$n = 1000$$

then after a time $nT = 10$ sec, the entire solution will have been plotted.

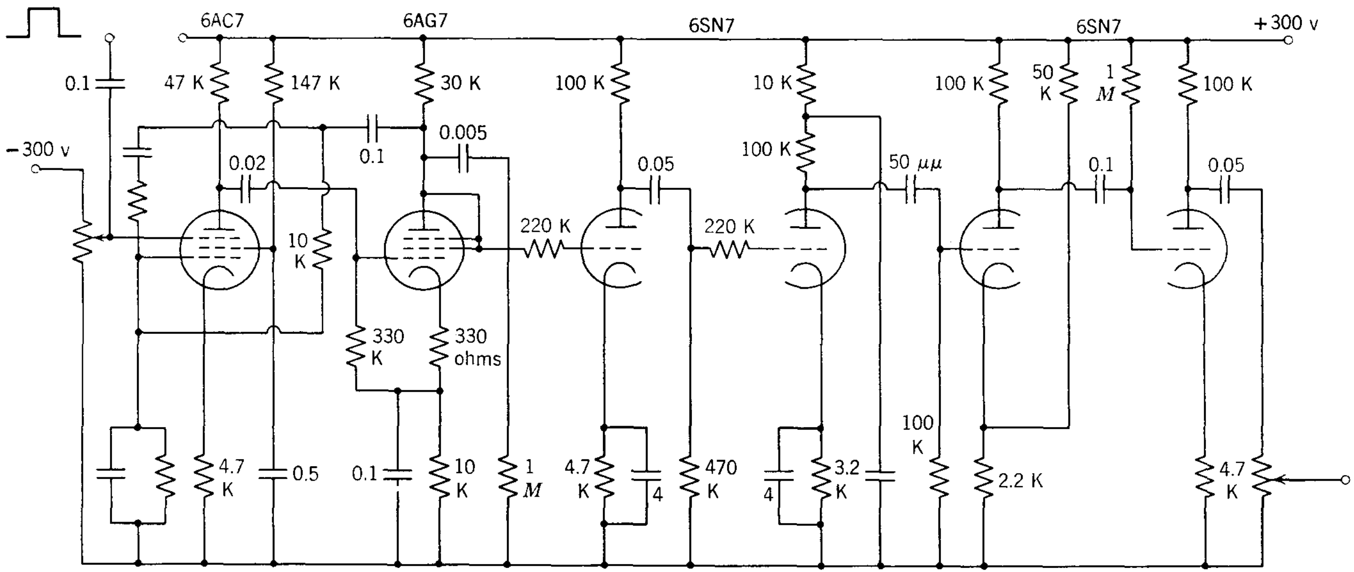

Fig. 7.6 Generator for time pulses (Indian Institute of Science).

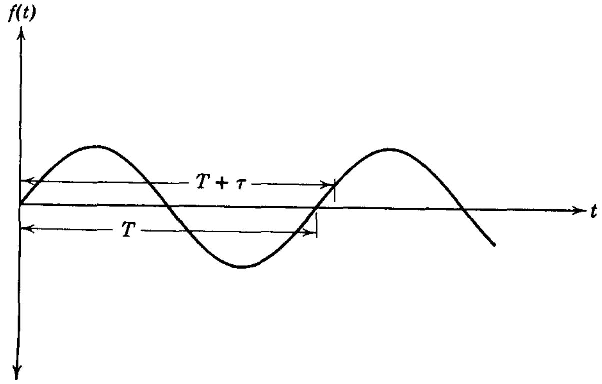

Fig. 7.7 Difference between sine wave period and repetition period for application of low-speed output equipment.

Thus, as far as the recorder is concerned the period of the solution is

$$T_1 = nT = 10 \text{ sec}$$

rather than 0.01 sec. By increasing n, the solution can be "slowed down" even more.

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