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The approximation of nonlinear functions in analog computers is currently accomplished by means of function generators of different types, of which the diode function generator is most commonly used. Disadvantages of this and other types of such equipment are overcome to a large extent by the triode-diode function generator developed at APL for use in the Laboratory's analog computer facilities.

A Triode-Diode Function Generator

To “build a better mousetrap” is the goal of every engineer. In analog computers, the “mousetrap” may take many forms, but the device that has had the most imagination applied to it is the general-purpose *function generator* that can simulate, with a high degree of accuracy, the nonlinear functions that are characteristic of modern physical systems. Two recent entries in this field are the triode and triode-diode generators, the principle on which they are based having been described first by L. V. Medredev *et al.*¹

The reason for so much activity in the search for more efficient function generators is that existing devices suffer from such disadvantages as limited frequency response, low precision, excessive drift, limited range, or difficulty of adjustment. *Diode* function generators, which are now the most generally used, are limited in the change of slope of the output that can be generated without seriously increasing drift and noise. *Triode* function generators are essentially unlimited in maximum slope and the change of slope.

A *triode-diode* function generator that overcomes the more serious drawbacks of earlier designs has recently been developed, built, and evaluated at APL for use in the Laboratory's analog computer facilities.² The principle of operation, based on that of the triode function generator, together with some of the characteristics of this equipment, will be briefly discussed. Operation of the diode and triode function generators will be explained as an aid in this description.

One of the major uses of the analog computer is to simulate a physical system, as, for example, a missile control loop or guidance system. Because most physical systems are by nature nonlinear,

in order to study such a system completely it is necessary that the computer generate the correct nonlinearities. These, unfortunately, may differ considerably from one another, depending upon the system. It is therefore desirable to have a single function generator that will generate all possible types of functions, or at least all of one class.

The breakdown below shows the groups of general-purpose function generators now in use.

GROUP	ACCURACY	BANDWIDTH
Electromechanical	high	low
Photoformer	low	high
Gain-switching	medium-high	medium
Digital or hybrid	medium-high	medium-low

The gain-switching group contains the popular diode function generator and the triode and triode-diode function generators.

Gain-Switching Function Generators

Gain-switching function generators use as their basic unit an operational amplifier whose closed-loop gain is changed abruptly at selected values of the input voltage. Thus, the output voltage as a function of the input appears as a continuous curve made up of straight-line segments. Members of this group can generate only single-valued functions of one variable.

The operational amplifier is the heart of the function generator as well as being one of the most important parts of the analog computer. It is a device whose output voltage is equal to the input, multiplied by the negative ratio of the feedback and input impedances. When these impedances are resistors, as shown in Fig. 1, the closed-

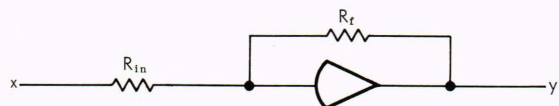


Fig. 1—Diagram of an operational amplifier.

¹ L. V. Medredev, A. A. Feldbaum, and L. N. Fitsner, “Single-Input Nonlinear Converters, *Automation and Remote Control*, 18, Oct. 1957, 945.

² C. J. Nisson, “An Analog Triode-Diode Function Generator,” Unpublished Master's thesis, University of Maryland, 1963.

loop gain (the ratio of y to x , the output and input signals, respectively) is equal to the negative ratio of R_f to R_{in} . In gain-switching function generators, the effective ratio of R_f to R_{in} is changed as a function of the input voltage amplitude by the operation of voltage-controlled switches. This has the effect of changing the slope of the input-output curve each time a switch is operated. In the diode function generator, the effective value of R_{in} is usually changed (some functions can be generated by changing R_f). In the triode function generator, R_f is varied, whereas the triode-diode function generator combines both techniques.

Diode Function Generator

The general-purpose diode function generator uses an operational amplifier as a summing device to add several voltages in order to approximate some desired curve. These voltages may consist of a constant voltage, a linear voltage, and several piecewise linear voltages as a function of the input signal x . The piecewise linear terms result from the operation of biased diode switches that either connect or disconnect input resistors to voltage sources whose values are sums or differences of V_i and x . The V_i terms are constant voltages, or biases, of either polarity, which are added to make the diode switches operate at desired values of x . The slope of the output in any piecewise linear region may be defined by the ratio of Δy to Δx . In terms of Fig. 2, this slope is equal to the negative ratio of R_f to R_{in} , where $R_{in} = R_1 R_2 / (R_2 - R_1)$; R_1 and R_2 are the effective parallel combinations of input resistors from x and $-x$, respectively. At each value of x , at which a diode switch connects or disconnects an input resistor R_i (one of several resistors in R_1 or R_2), the slope of the output changes by the amount R_f/R_i . The direction of the change in slope depends on the polarity of the connections of the diode in question and on the polarity of its biased source. A combined biased diode and input resistor is necessary for each change in slope desired.

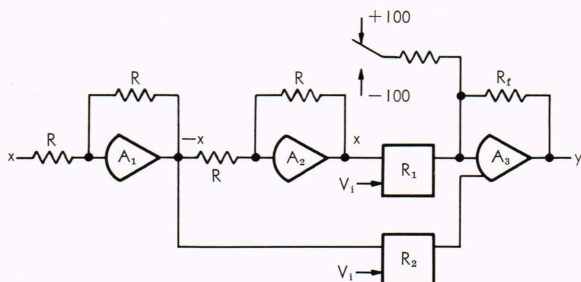


Fig. 2—Diagram of a diode function generator.

One of the major disadvantages of this function generator is that to generate a steep slope or a large change in slope, input resistors must be made small. However, because there is a minimum value allowable as a result of the limited current capabilities of the amplifiers, there will be a limit on maximum slope and slope change. For most commercial diode function generators the limit on slope change is between 5 and 20 volts per volt.

Triode Function Generator

Consistent with the function generators of its class, the triode function generator produces a piecewise linear output by changing abruptly the gain of an operational amplifier as a function of the input voltage. In this case, triode switches are used to change the feedback resistor.

Operation of the triode switch is quite different from that of the diode switch. The triode switch is a simple triode amplifier driven from beyond cutoff to saturation. It approximates a single-pole, three-position, voltage-controlled switch because (1) its plate voltage is at ground when the tube is cut off, (2) it varies linearly with the input when it is conducting, and (3) it is clamped at -100 v as it approaches and after it reaches saturation.

A diagram of the triode function generator is shown in Fig. 3. In this diagram, A_1 is a high-gain-chopper, stabilized, DC amplifier whose third stage is one of the switching triodes T_i in the second position. In this circuit, the plate of the switching triode acts as the output of the gain-controlled amplifier. Its voltage is equal to $-(R_{fi}/R_i)(x + V_i)$, where V_i is equal to R_1 multiplied by the sum of all currents flowing into the summing node of A_1 from fixed sources; i.e., $X_o/R_o - 100/R_{f1} - \dots - 100/R_{fi-2} - 100/R_{fi-1}$.

The switching triodes are controlled by the tapped divider R_d so that they operate sequentially. When x has its minimum value (x_{min}), the plates of all switching triodes are at ground potential. When x is increased slightly, the triode T_1 whose grid has the most positive bias will start to conduct, and its plate will operate as the output of the gain-controlled amplifier. When x is increased, this voltage will decrease linearly until it is clamped at -100 v. As x is increased infinitesimally beyond this point, the second triode switch will start to conduct and have its turn as the output stage. This procedure will continue as x increases until all triode switches have reached -100 v.

The output voltage y will be the sum of the voltages from the switches after they have been multiplied by the associated K_i factors. When x has its minimum value, y will equal $100 K_o$. As x increases, y will vary with piecewise constant slopes

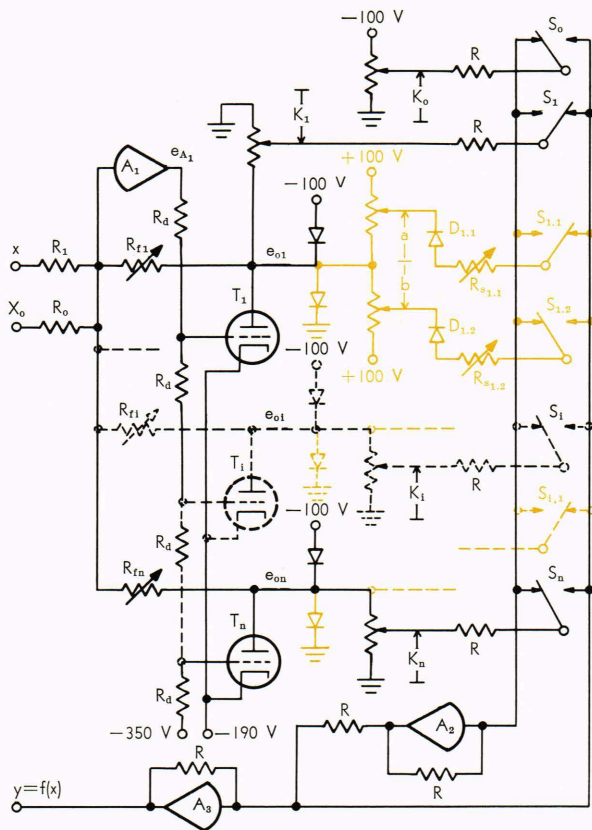


Fig. 3—Diagram of a triode function generator (in black), and showing (in color) the additional circuitry required to make a triode-diode function generator.

until all switches have been turned to -100 v. The slope of y will change each time a new triode saturates. The slope m_1 of the i^{th} segment is $K_i (R_{fi}/R_1)$, where K_i may have any value between ± 1 (see Fig. 4). The value of R_{fi} is adjusted to determine the length of the i^{th} linear segment of the output voltage.

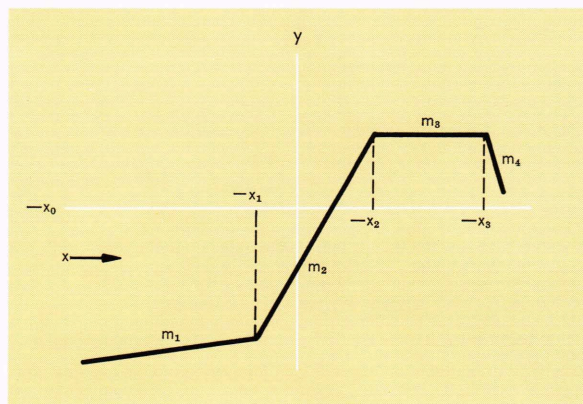


Fig. 4—Triode-function-generator output versus input.

This function generator has the advantage that very steep slopes can be generated by making K_i unity and R_{fi} large. By disconnecting R_{fi} , the slope of the i^{th} segment will approach infinity, making it possible to generate discontinuous functions. This type of generator is also more convenient to adjust because the slope of each segment is independent of other segments. Some of the disadvantages are added complexity and the need for a special amplifier A_1 .

Triode-Diode Function Generator

By combining the techniques used in the diode and triode function generators, additional slope changes may be obtained economically. This simply requires adding diode switches to the plates of the switching triodes (Fig. 3). The diode-controlled input resistors may be connected manually to either amplifier A_2 or A_3 . The purpose of these diode switches is to modify the slope of the triode segment to which they are slaved. The slope change that can be generated by the diode segments is again limited, but the slope of the triode segment may still range from zero to near infinity.

The advantage of this function generator over the triode function generator is in the economy of obtaining additional line segments in the output. The cost is some loss of flexibility and an increase in setup time.

To use the APL-designed triode-diode function generator with the analog computer requires only one input and two output connections. The latter go to the summing junctions of A_2 and A_3 , which are standard computer amplifiers. Adjustment of the unit to generate a given function is straightforward and consists merely of setting potentiometers and closing toggle switches. Given a set of desired breakpoints and slopes, a 20-segment output function can be set up and checked with a digital voltmeter in 15 minutes.

The potentialities of the triode and the triode-diode function generators are good because of their ability to generate steep slopes and the relative ease with which they may be adjusted. Errors due to drift, noise, and reduced bandwidth are generally slightly greater than for the diode function generator, depending somewhat on the function being generated.

The principle of changing the feedback resistor, as used in the triode function generator, might easily be extended to equipment using transistor operational amplifiers. Here, the triodes could be replaced with common emitter amplifiers. In fact, both PNP and NPN transistors might be used with plus and minus reference voltages, making bipolar feedback possible.