Introducing....

PEAC

A low cost, general purpose analogue computer of modern design, intended for the amateur or student.

A useful tool which is capable of solving complicated problems at high speed.

Can be used as a model to simulate mechanical systems and electronic networks.

Extends enormously the scope of the amateur experimenter.

This series of articles will explain in detail the design, construction, and operation of PEAC.

ANALOGUE

Most of the publicity afforded to computers favours digital equipment. However, digital methods tend to be disproportionately expensive for small installations. On the other hand, although analogue equipment is ideally suited to limited, low-cost applications, it was not until the silicon transistor had become firmly established, and enough practical published information was available, that a start could be made on designing analogue computing equipment to yield a reasonable standard of performance in the lowest possible price range.

A WORTHWHILE PROJECT

No doubt many readers will think that construction of a true computer could involve them in a great deal of time, money, and effort. They might also believe that an average understanding of mathematics would not be sufficient to equip them to operate a computer effectively. However, the amount of time and money spent building PEAC need be no more than is consumed by a home constructed hi fi outfit of normal proportions and performance, and the computer will solve even simple problems a great deal faster than the human mind or slide rule, once it has been programmed to do so.

In fact, a general purpose computer can find application in almost every sphere of technical activity, and is particularly useful in the electronic workshop, to the point of becoming indispensable after a short period of use.

UNIT CONSTRUCTION

PEAC is arranged in the form of units, and is organised in such a way that reasonably advanced computations may commence upon completion of the first unit, UNIT "A". The cost of building UNIT "A", based upon typical retail prices at the time of writing, will not be much above £25, and yet it will solve algebraic polynomial equations, simultaneous linear equations, simple differential equations, and can also be used to simulate the behaviour of many elementary mechanisms and electronic networks.

UNIT "A" is designed primarily to satisfy a minimum user requirement, for experimental and educational work, but it also serves as a convenient starting point for the addition of further units to expand the computer to almost any desired degree of capability and complexity. The additional facilities provided by the add-on UNITS "B", "C", and "D" are described in the specification. See also the block diagram, Fig. 1.1.

A comprehensive PEAC installation, equipped with a function generator and multiplier, and with full integrating facilities for the fast solution of a range of differential equations, might finally cost around £60: not a lot to pay for an item of workshop equipment which can solve electronic formulae in 10ms, and which may also be employed as a variable waveform generator, 18 input high quality audio mixer, variable characteristic high Q audio filter, large inductance or capacitance simulator, d.c. or a.c. millivoltmeter, and many other things besides.

COMPARISON BETWEEN ANALOGUE AND DIGITAL COMPUTERS

Although popularly regarded as an inaccurate machine of limited usefulness, the analogue computer is to be found in the Polaris missile, spacecraft, aircraft, large scale chemical processes, and many automated production lines, quite apart from basic research work, where flexibility and ease of working are often considered to be more important than extreme accuracy. The analogue computer is, in most cases, very much faster than its digital counterpart, and can offer far more in the way of general facilities for a given outlay.

The time taken to solve a problem on an analogue computer is independent of problem length. All circuits operate in parallel, simultaneously. A typical solution might be arrived at in 20ms, and this solution can then be repeated at the rate, say, of 25 solutions per second. In human terms the solution is virtually immediate and continuous, therefore, any adjustments made to problem parameters (terms of an equation) while the computer is working will be immediately reflected in the solution readout. This rapid response allows the operator to quickly gain an insight into the workings and structure of a problem.

In contrast, digital computers perform many mathematical operations in a pre-determined and comparatively lengthy sequence, which bears little obvious relationship to the structure of the problem, but they do offer the very high degree of accuracy essential for calculations involving money or very precise data.

The computer of the future will undoubtedly combine the best of both worlds with analogue and digital equipment in hybrid form.

ANALOGUE METHODS

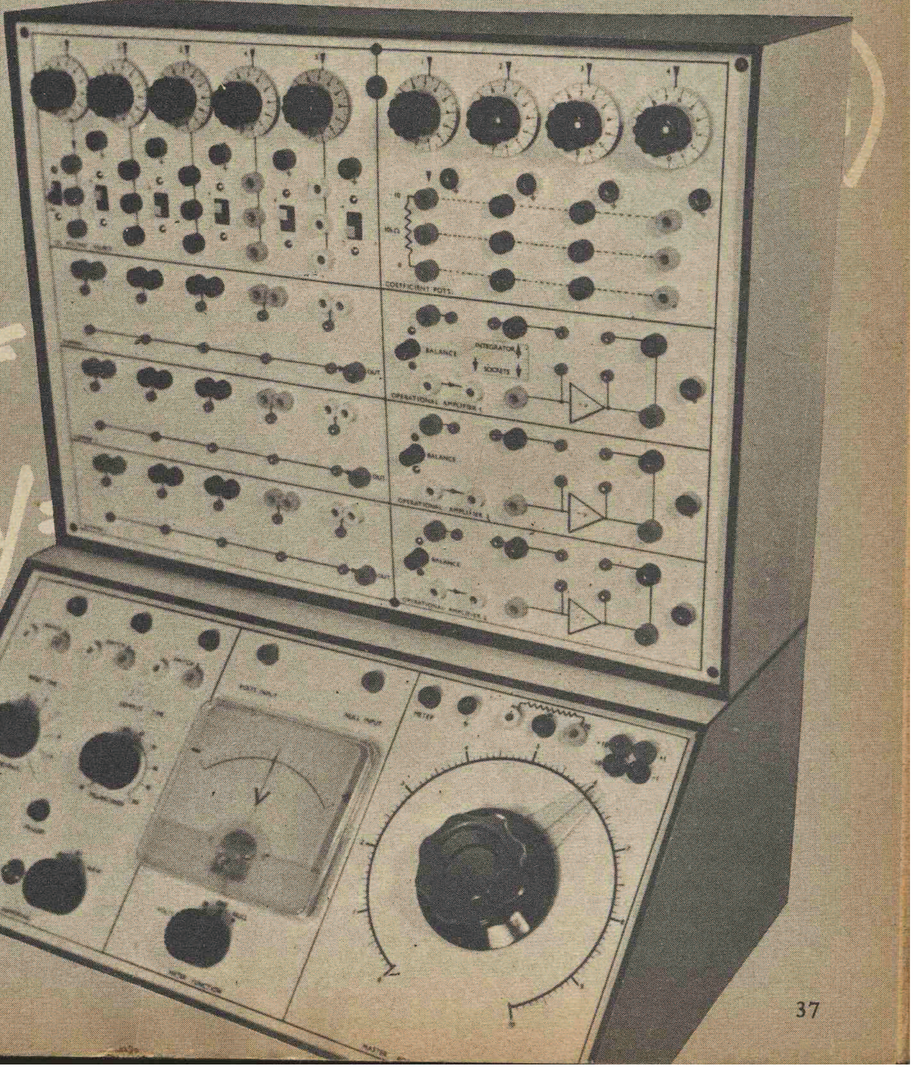
The statement that an aeroplane is a machine for solving sets of differential equations is not very far removed from the truth. If the aeroplane did not solve its equations correctly it would not be able to fly at all. Almost all relationships or events can be described mathematically, or in turn be represented by an analogy. A model aeroplane in a wind tunnel solves, by analogy, roughly the same equations which govern the behaviour of the real aeroplane, although in much simpler and less expensive fashion.

An analogy of a physical or mathematical process could be achieved by a system of gears, pulleys, and levers; or by the controlled flow of gases or liquids. But in the last couple of decades electronic methods of simulation and equation solving have become almost universal, because of the accuracy, availability, and adaptability of standard electronic components.

The main purpose of the analogue computer is to allow a model to be set up quickly and easily, to simulate the behaviour of a full scale system, and at

COMPUTER

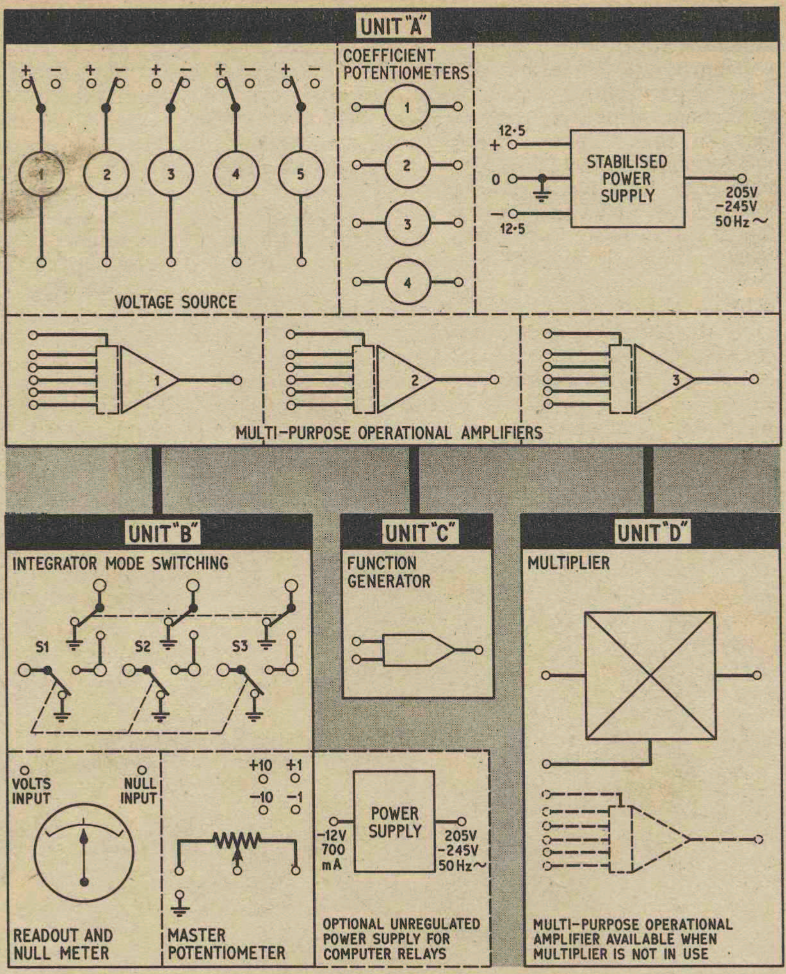
By D.BOLLEN



The Practical Electronics Analogue Computer is of flexible design. The basic equipment is UNIT "A". Computing facilities may be extended by the addition of further units: "B", "C" and "D", in accordance with user requirements.
This photograph shows UNIT "A" standing on UNIT "B"

Fig. 1.1 Block diagram of

PEAC



SPECIFICATION

UNIT "A"

POWER SUPPLY

Input 205V—245V 50Hz. Output ±12·5V d.c. Voltage regulation better than 1% for loads of 0—200mA, and 2% for 0—300mA. Total ripple 2mV. Complete short circuit protection.

AMPLIFIERS

Three multi-purpose operational amplifiers, each with five silicon transistors. Open loop voltage gain greater than 5,000. Output ±10V at 5mA. Current demand (average) 40mA. Equivalent input drift under normal room conditions better than ±0·5mV per hour. Unity gain frequency response within 1% for 0—10kHz, and 5% for 0—25kHz. Typical noise and hum at output 3mV.

VOLTAGE SOURCE

Five independent outputs, each continuously variable in three steps giving ±0—0·1V, ±0—1V, and ±0—10V. Dial setting accuracy better than 3% of full scale between dial divisions 1—10. Total current demand 50mA.

COEFFICIENT POTENTIOMETERS

Four 10 kilohm 270° potentiometers. Dial setting accuracy better than 5% of full scale between dial divisions 1—10.

SUMMING NETWORKS

Three five-input summing networks provided with voltage check sockets, and plug-in computing components.

UNIT "B"

MASTER POTENTIOMETER

25 kilohm 300° wirewound; 25 watt. Two voltage measuring ranges ±0—1V and ±0—10V. Scale length 14in. Accuracy better than ±0·5% of full scale.

READOUT METER

Centre zero 100—0—100μA, calibrated 0—0·3V, 0—1V, 0—3V, and 0—10V. Accuracy better than ±2% of full scale.

INTEGRATOR SWITCHES

Provision for three or more integrating amplifiers. Compute times ranging from 10ms—1s. Single shot or repetitive mode with "hold" facility. Current demand around 65mA.

UNIT "C"

FUNCTION GENERATOR

Diode function generator for parabolic and other functions. Typical accuracy 2%. Frequency response to several kHz.

UNIT "D"

MULTIPLIER

Four quadrant multiplication of two or more variable voltage inputs. Also incorporates an operational amplifier which may be used on its own to supplement the amplifiers of UNIT "A". Frequency response generally better than 0—50Hz. Approximate current demand around 75mA.

the same time solve the equation which represents the system. Sometimes the computer will be used just for solving equations or, alternatively, as a working model only, depending on the nature of the problem. The advantage of the electronic computer is that it will do each, or both at the same time, with ease.

The computer is set up, or "programmed", for a particular task by inserting computing components, i.e. resistors and capacitors, into sockets on the front panel. This procedure will be described in full detail in due course.

ANALOGUE COMPUTER CIRCUITS

In the electronic analogue computer, the analogy is created fundamentally by manipulating sets of d.c. voltages. There is nothing to prevent a.c. voltages being used—in fact they often are—except that a.c. measurement techniques are generally less accurate at low levels than d.c. However, when simulating dynamic processes with d.c. voltages, the computer will be handling a voltage which varies with time. In this context it is more appropriate to regard a waveform, even if it is a pure sinewave, as a d.c. voltage varying with time according to a formula which describes the nature of the waveform.

The main computing element is the "operational amplifier". As far as operational amplifiers are concerned, the decibel is much too coarse a unit to use for the measurement of frequency response, so amplitude linearity is usually expressed as a percentage variation over a fairly restricted range of audio frequencies. In some cases, for example, an operational amplifier and its attendant circuits will be expected to respond to inputs from d.c. to 5kHz with an accuracy of a fraction of 1 per cent, and up to 10kHz at no worse than 1 per cent.

COMPUTING ELEMENTS

The majority of problems can be solved by the varied application of only five analogue elements, but the size of the problem to be handled will in turn depend on the quantity of elements available, and hence on the overall size of the computer.

The five computing elements are shown in Fig. 1.2, together with their conventional symbols and generalised functions. The symbols are used as a kind of shorthand when drawing up a computer programme.

The first thing to note about the simplified circuit diagrams of Fig. 1.2 is that the common earth return is often completely ignored. Computer supply voltages are usually positive and negative in relation to an earthed centre tap. Since the input and output terminals of each computing element are arranged to be very close to earth potential in the absence of an input voltage, it is feasible to take the earth rail for granted and regard all circuits as having only two terminals, instead of the usual four.

Although the symbol and function of each of the elements of Fig. 1.2 are common to all analogue computers, the actual circuit design and choice of components will naturally vary from one computer to another. For example, the time-division multiplier of Fig. 1.2e is only one among many possible circuit configurations for achieving multiplication of independent variables. Alternative approaches include the Hall effect, the servo, logarithmic, and quarter square multipliers.

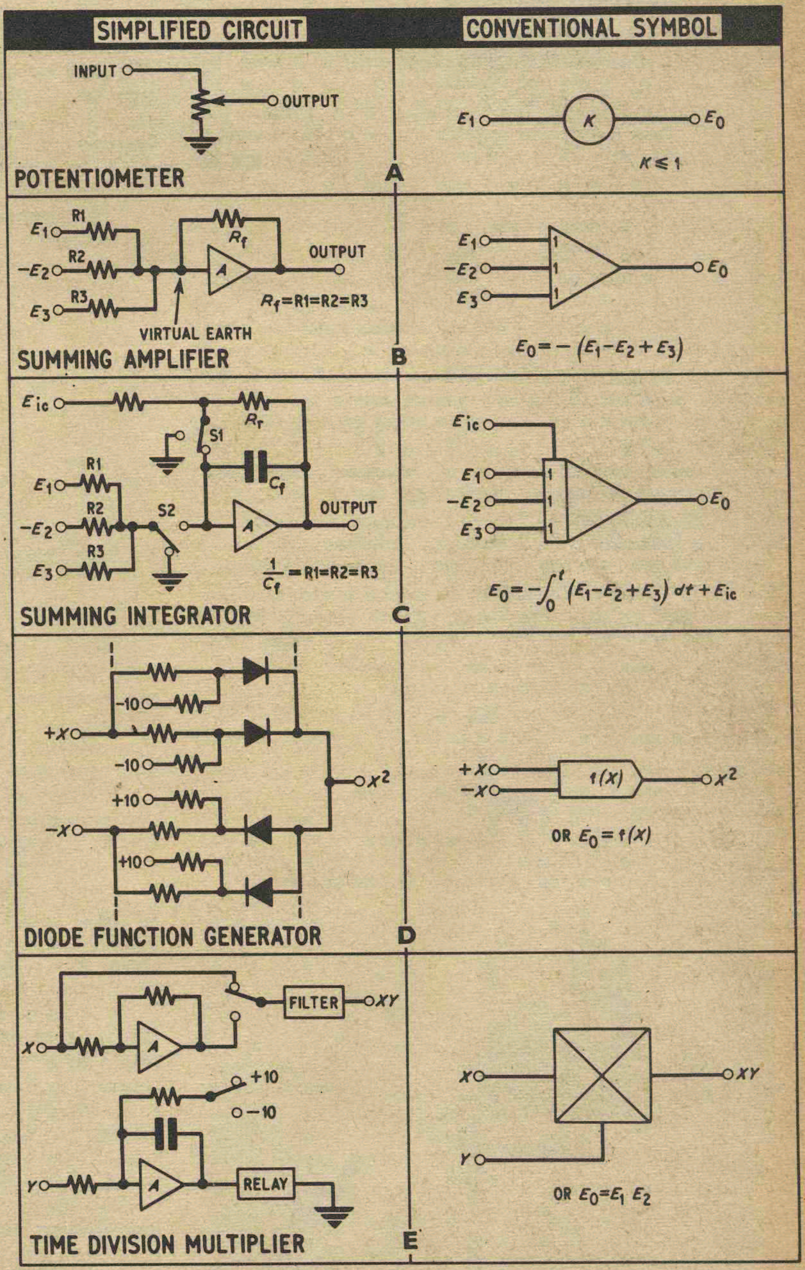


Fig. 1.2 Analogue computing elements

It is proposed to examine computing elements in greater detail when they are dealt with individually at a later stage, but in the meantime a brief survey will suffice.

COMPUTING POTENTIOMETER

The potentiometer of Fig. 1.2a may be used for multiplying a variable voltage (often called a machine variable) by a constant of less than unity.

Example: potentiometer input 1·5 volts. Slider set exactly half way along resistance track, corresponding to a constant of 0·5. Output voltage E_o therefore equals 1·5 × 0·5, or 0·75. As set, the potentiometer will multiply any input voltage by 0·5.

When incorporated in the feedback loop of an operational amplifier, the potentiometer will divide a machine variable by a constant smaller than 1. The fact that potentiometer constants are less than unity is no real disadvantage. It is a simple matter to either increase input voltages by a factor of ten, or increase the gain of an operational amplifier ten times, to bring the potentiometer constant above unity. Like the slide-rule, it is simply a matter of deciding in advance where the decimal point should be.

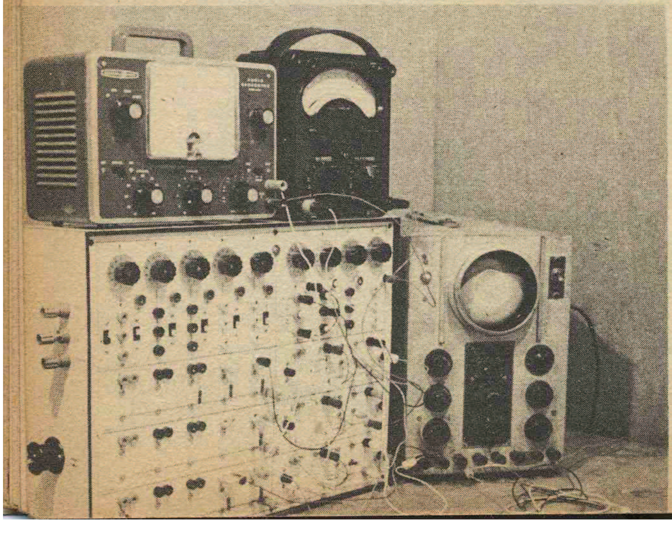
SUMMING AMPLIFIER

The summing amplifier of Fig. 1·2b uses a high gain operational amplifier with several inputs to achieve addition and subtraction of machine variables. When the operational amplifier has a voltage gain equal to several thousand, input voltages will be accurately summed together, without unwanted interaction. The summing junction SJ is at "virtual earth", a way of saying that SJ will never be more than a few millivolts above or below earth potential, and is also, to all intents and purposes, shunted by a resistance of only a few ohms. Compared with input resistors R1–R3, the SJ shunt resistance is very low indeed, a condition necessary for accurate summing of voltages.

A definite relationship exists between resistors R1–R3, and feedback resistor R_f, and if these resistors are arranged to plug into the amplifier, many problem conditions can be met by "ringing the changes" on preferred values of fixed resistor, including multiplication by a constant as well as addition.

If a voltage E_1 is applied via resistor R_1 (in Fig. 1.2b) ot the summing junction SJ, the output voltage E_o will be $-E_1 \frac{R_f}{R_1}$. The operational amplifier is designed to invert an input voltage, hence the minus sign in front of this expression. The ratio between input resistor and R_f holds good for each input.

This photograph shows UNIT "A" being used to simulate a tuned LC circuit, consisting of an inductance of 5H in series with a capacitance of 5μF. The oscilloscope is displaying phase shift within the simulated circuit at the resonant frequency of 31Hz, and the trace also gives an indication of the damping factor or "Q" of the circuit



Example: apply three input voltages $E_1 = 5$, $E_2 = -3{\cdot}5$, and $E_3 = 2$ to the summing junction via $R_1 = 10$ kilohm, $R_2 = 2$ kilohm and $R_3 = 100$ kilohm. Let the feedback resistor $R_f = 10$ kilohm. The relationship between voltages and resistances will be

$$E_o = -\left(E_1\frac{R_f}{R_1} - E_2\frac{R_f}{R_2} + E_3\frac{R_f}{R_3}.\right)$$ Substituting values

$$E_o = \left(5\frac{10}{10} - 3{\cdot}5\frac{10}{2} + 2\frac{10}{100}\right) = (5 - 3{\cdot}5 \times 5) + 0{\cdot}2),$$

therefore $E_o = 12{\cdot}3$.

In the above example, the summing amplifier has not only summed negative and positive inputs, but has also multiplied E_2 by 5, and E_3 by a constant of 0·1, merely by selection of appropriate values of input resistor.

SUMMING INTEGRATOR

The summing integrator is used for the detailed investigation of time dependent variables, and for the solution of problems involving calculus.

The integrator of Fig. 1.2c is based on the inverting operational amplifier, with capacitor C_f acting as the feedback component. The output from a single integrator, in response to a steady voltage input, is a linear ramp voltage which increases with time at a rate dependent on choice of input resistor, feedback capacitor, and input voltage. Once again, precise relationships must exist between computing components and voltage, but now time is introduced as an additional analogue variable.

The action of electronic integration is best explained by a working example, and reference should be made to the diagram of Fig. 1.3a.

Example: a fairly sluggish motor car accelerates from rest at a steady rate of 20ft/second/second. Examine the progress of the motor car during the first four seconds of its motion. The computer is set up to operate in "real time", that is to say, the time actually occupied by the motor car when accelerating. The problem layout of Fig. 1.3a shows a computing potentiometer "A" coupled to the input of Integrator "1", which in turn feeds Integrator "2". Voltmeters are connected into circuit to display the three parameters of interest. Potentiometer "A" is first adjusted so that its dial reads 2, corresponding to multiplication by the constant 0·2, to represent 20ft/s^2 scaled down to yield a voltage of appropriate magnitude for the integrators to handle. The output from the potentiometer is a steady voltage analogue of a steady rate of acceleration.

As soon as switch S3 is closed to the +V position, the velocity and distance meter pointers will start to move in a manner analogous to the motion of the motor car. Velocity will increase linearly with respect to time, while distance will be displayed as an accelerating pointer movement. Integrator "2" computes distance (s) as a voltage function of the square of time, in terms of $s = \frac{1}{2}at^2$.

With the problem of Fig. 1.3a, acceleration, velocity, and distance are immediately available to the computer operator as dial and meter readings. He can vary acceleration just by turning the dial of the potentio-

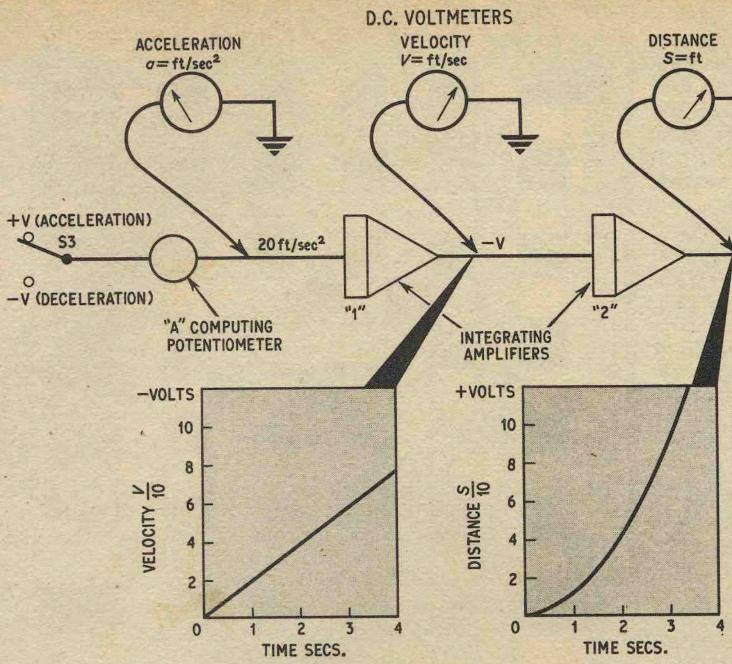


Fig. 1.3a (left). The use of integrators is illustrated in this diagram. In this example the rate of acceleration, velocity, and distance covered by a motor car are computed and can be read off the potentiometer dial and meter scales

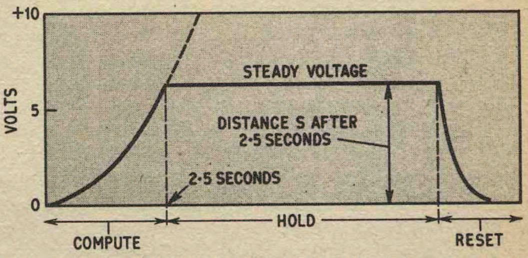


Fig. 1.3b. Arresting a computation to give a steady voltmeter reading

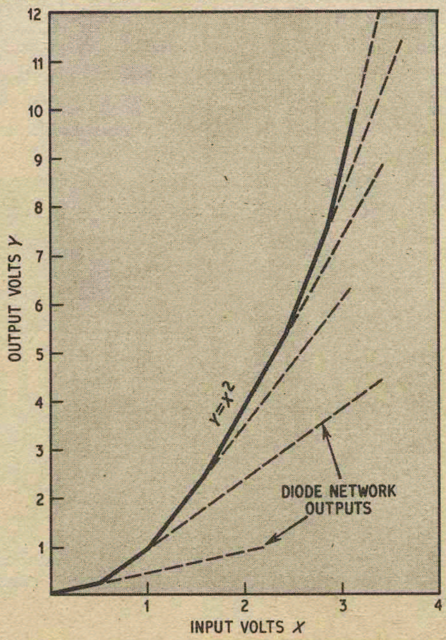
meter. If switch S3 is moved to the −V position, the car will decelerate and stop.

COMPUTE, HOLD AND RESET

It is obviously inconvenient to take readings from voltmeters when pointers are on the move, and it is impossible to do so if time t is very short, as with fast events, or when the computer is speeded up to some fraction of real time. The sequence governing switches S1 and S2, in Fig. 1.2c, is therefore arranged to provide three facilities, called "compute", "hold", and "reset".

The purpose of the "hold" facility is to allow a steady meter reading to be taken at any point on the voltage/time curve output of an integrator. The high gain introduced by the operational amplifier effectively multiplies the capacitance of C_f when the integrator input is disconnected from input resistors and reset resistance R_r. With amplification, C_f becomes the equivalent of a very large capacitor which is capable of holding a charge for a relatively long time. In practice, the ability of an integrator to "hold" or store a voltage will also depend on low amplifier drift.

Fig. 1.3b shows graphically the effect of compute, hold, and reset modes, when applied to the distance curve of Fig. 1.3a. In this case, it is necessary to halt the computation after an elapsed time of 2·5s, and obtain a value for distance in the form of a steady meter reading.



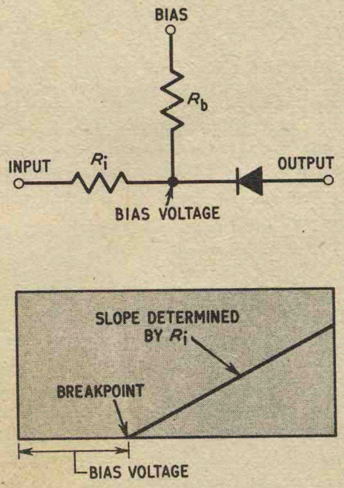


Fig. 1.4a (left). Illustrating how a mathematical function can be constructed from a series of straight line tangents

Fig. 1.4b (above). A single diode network and its output characteristic

The compute mode is initiated by opening S1 and closing S2 (Fig. 1.2c). After 2·5seconds, S2 automatically opens and the amplifier input is left floating, with C_f still connected between input and output and holding a stored charge. A meter coupled to the integrator output will show the distance travelled after 2·5s of acceleration.

The "hold" period can occupy several tens of seconds, and is usually at the discretion of the operator. To begin a new computer run, S1 is closed, discharging C_f through R_r, thus resetting the integrator output to zero. The input E_{ic} in Fig. 1.2c, is to allow an initial condition to be applied to the integrator, as in the case of a motor car which does not start from rest, but is already in motion when it accelerates. When computing and resetting times are shorter than about 1s, voltmeter answers will appear to be given at the instant of pressing the button which initiates the S1, S2 cycle.

The above description relates to a "single shot" computer run, where the operator adjusts, takes a reading, adjusts, and so on. In the repetitive mode, the hold facility is ignored and the computer keeps on repeating the answer curve, for display on an oscilloscope, chart recorder, or XY plotter.

DIODE FUNCTION GENERATOR

In many computer applications it is necessary to generate a voltage which varies according to some non-linear function not provided by normal operational amplifier techniques. The diode function generator of Fig. 1.2d will allow a mathematical function to be constructed from a series of straight line tangents, as shown in Fig. 1.4a.

Each straight line characteristic is obtained from a single diode-resistor network, and when the outputs from several networks are summed together a complete function will result. The shape of the final approximated curve is determined by adjustment of the network resistors. Apart from powers of x, and other functions, roots are achieved by placing the function generator in the feedback loop of an operational amplifier.

A single diode network appears in Fig. 1.4b, and the slope of its output characteristic can be varied by adjustment of R_1. The diode breakpoint (the voltage at which the diode starts to conduct) is dependent on the value of R_b.

MULTIPLIER

The computing potentiometer will multiply a variable by a constant, but special techniques must be used to multiply one variable by another variable. The process employed in modern computers is akin to modulation, where the gain of a circuit is controlled by an applied voltage.

The multiplier should yield a product of correct sign when multiplying negative or positive variables, and this is readily achieved with the self-excited time division circuit of Fig. 1.2e. The time division multiplier operates on the principle of modifying the mark-space and amplitude of a square wave in accord with two voltage inputs. The filter of Fig. 1.2e extracts the mean level of d.c. from the square waveform. An additional advantage of the Fig. 1.2e circuit is that it can be arranged to cater for more than two variables. For example, inputs $X1$, $X2$, and $X3$ multiplied by input Y.

Next month: Commencing the construction of UNIT "A".