

# 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.

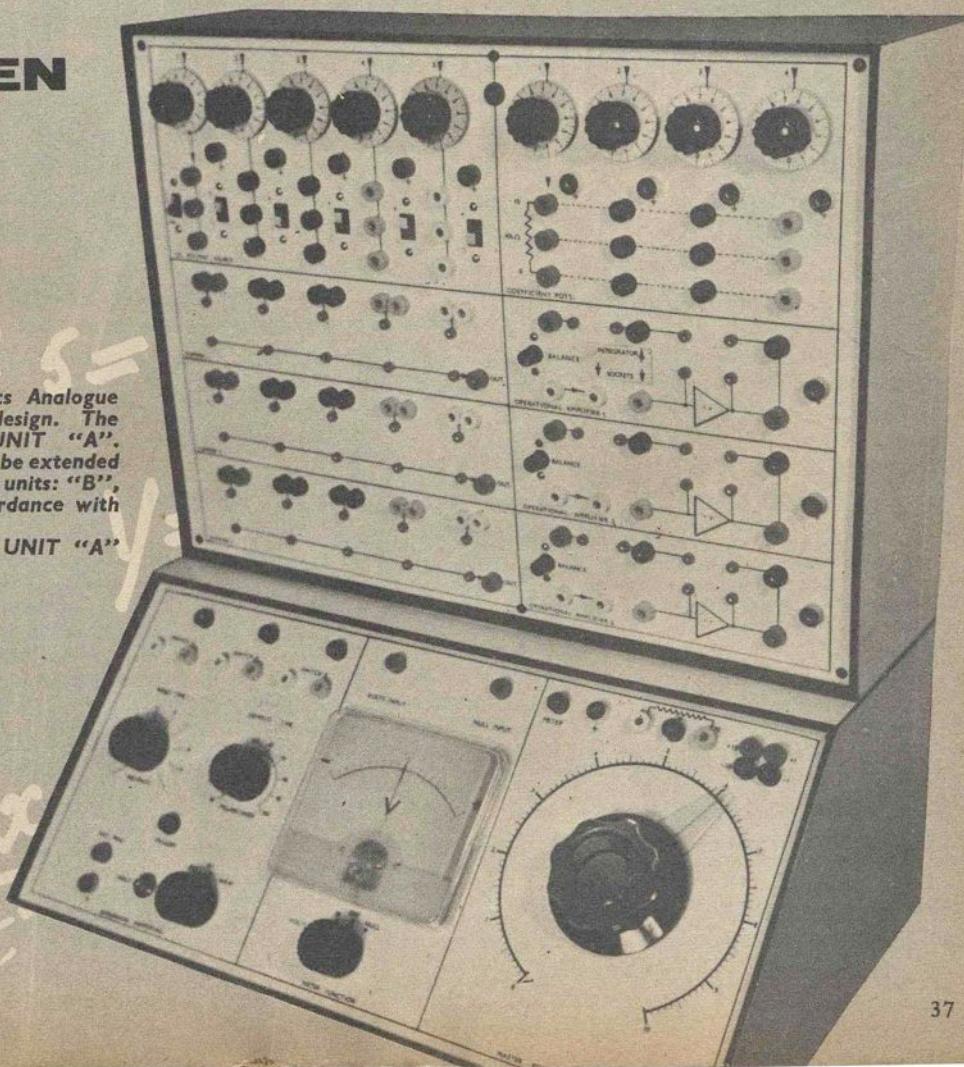
The main purpose of the analogue computer is to allow a model to be set up quickly and easily, to simulate the behaviour of a full scale system, and at

# 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  $\pm 12.5$  V 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  $\pm 10$  V at 5mA. Current demand (average) 40mA. Equivalent input drift under normal room conditions better than  $\pm 0.5$  mV 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

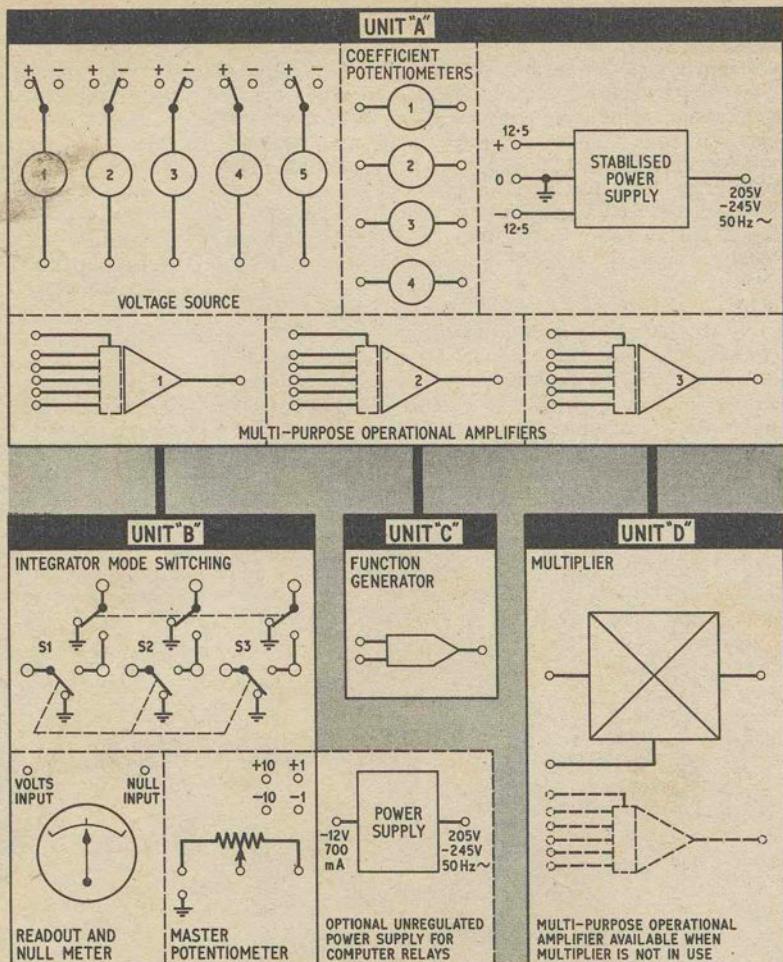
Five independent outputs, each continuously variable in three steps giving  $\pm 0$ — $0.1$  V,  $\pm 0$ — $1$  V, and  $\pm 0$ — $10$  V. Dial setting accuracy better than 3% of full scale between dial divisions 1—10. Total current demand 50mA.

#### 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  $\pm 0$ — $1$  V and  $\pm 0$ — $10$  V. Scale length 14in. Accuracy better than  $\pm 0.5\%$  of full scale.

#### READOUT METER

Centre zero  $100$ — $0$ — $100$   $\mu$ A, calibrated  $0$ — $0.3$  V,  $0$ — $1$  V,  $0$ — $3$  V, and  $0$ — $10$  V. Accuracy better than  $\pm 2\%$  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.

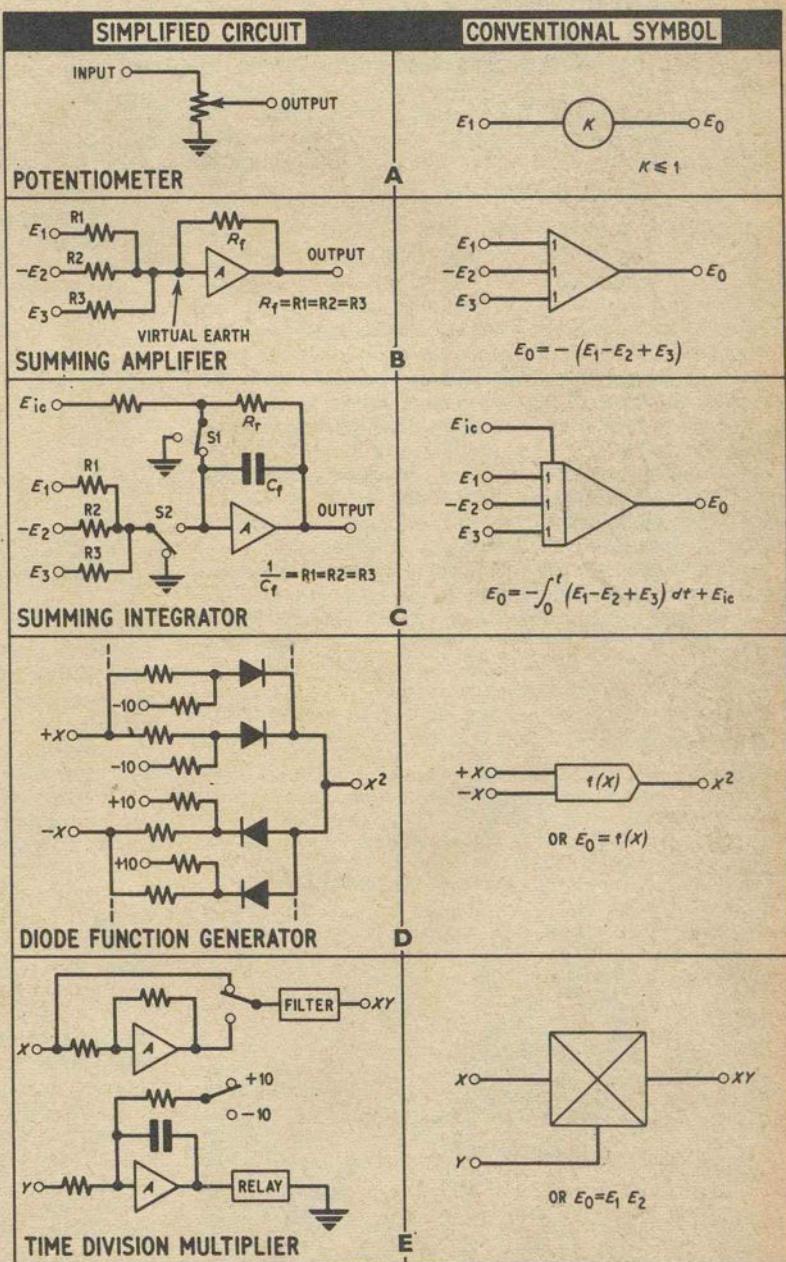


Fig. 1.2 Analogue computing elements

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  $1.5 \times 0.5$ , 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) to the summing junction SJ, the output voltage  $E_o$  will

*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*



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.

*Example:* apply three input voltages  $E_1 = 5$ ,  $E_2 = -3.5$ , 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

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

$$E_o = \left(5 \frac{10}{10} - 3.5 \frac{10}{2} + 2 \frac{10}{100}\right) = (5 - 3.5 \times 5) + 0.2,$$

therefore  $E_o = 12.3$ .

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  $20\text{ft/s}^2$  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 poten-

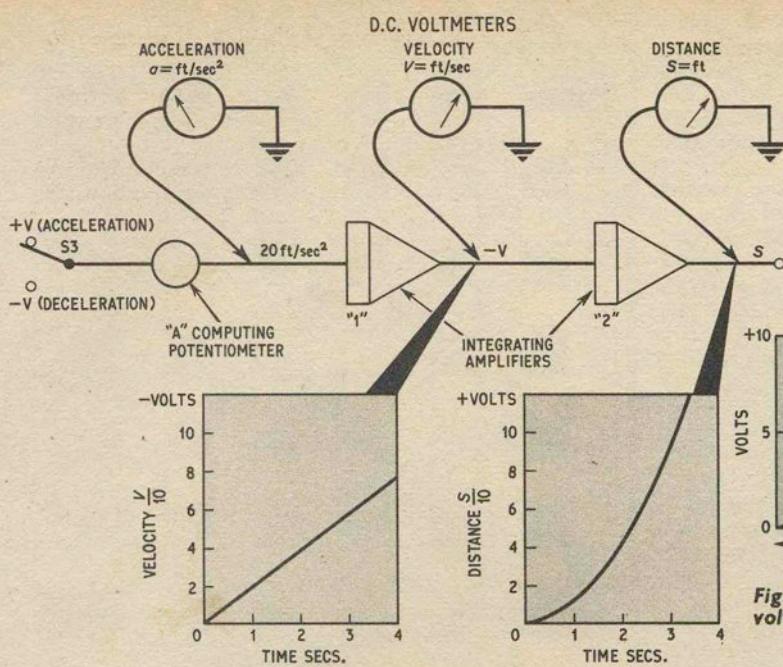


Fig. 1.3a (left). The use of integrators is illustrated in this diagram. In this example the rate of acceleration, velocity, and distance covered by a motor car are computed and can be read off the potentiometer dial and meter scales

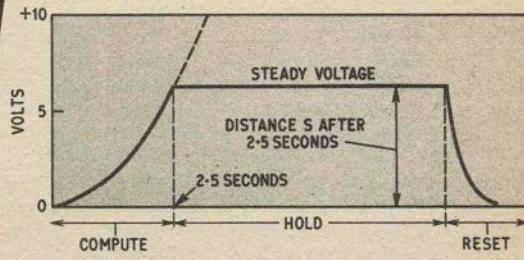


Fig. 1.3b. Arresting a computation to give a steady voltmeter reading

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

multiples the capacitance of  $C_I$  when the integrator input is disconnected from input resistors and reset resistance  $R_R$ . With amplification,  $C_I$  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.

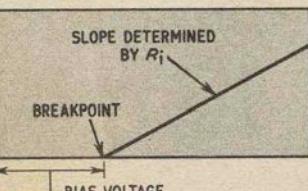
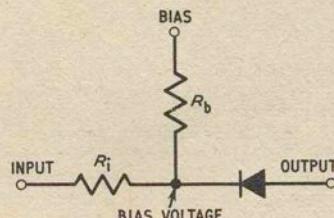
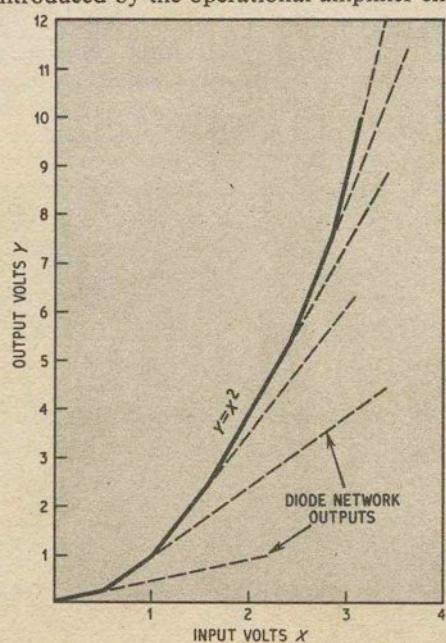


Fig. 1.4a (left). Illustrating how a mathematical function can be constructed from a series of straight line tangents  
Fig. 1.4b (above). A single diode network and its output characteristic

The compute mode is initiated by opening S1 and closing S2 (Fig. 1.2c). After 2·5 seconds, S2 automatically opens and the amplifier input is left floating, with  $C_1$  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  $C_1$  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.

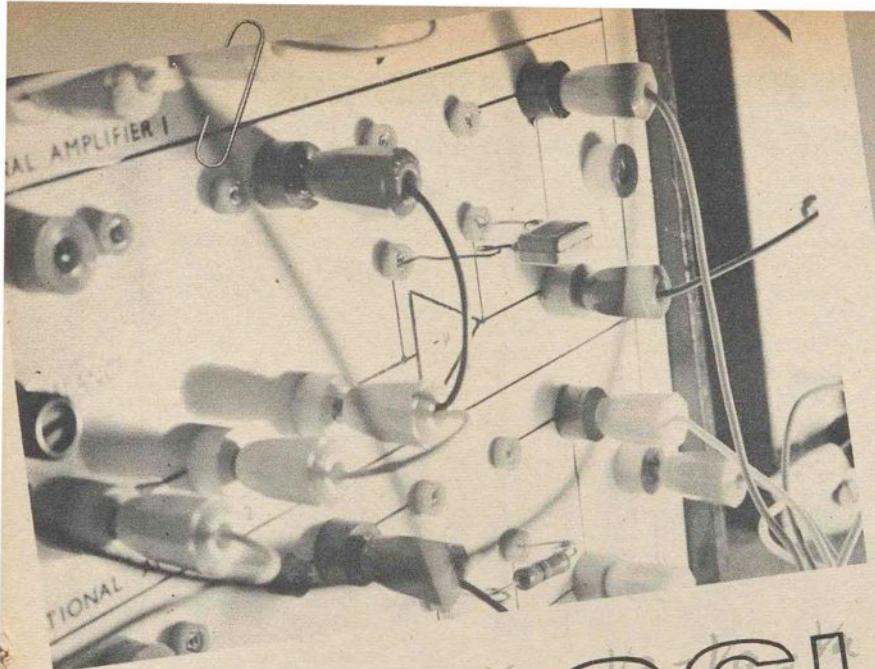
A single diode network appears in Fig. 1.4b, and the slope of its output characteristic can be varied by adjustment of  $R_1$ . The diode breakpoint (the voltage at which the diode starts to conduct) is dependent on the value of  $R_b$ .

#### 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  $X_1$ ,  $X_2$ , and  $X_3$  multiplied by input  $Y$ .

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



PEAC

# ANALOGUE COMPUTER

By  
D.BOLLEN

BEFORE embarking on constructional details, a few words must be said concerning measuring and test equipment required.

## VOLTAGE STANDARD

It is necessary, at an early stage of computer construction, to establish a voltage standard for setting up the PEAC circuits.

Since relative voltage levels are more important than absolute levels, one particular voltmeter of proven reliability can serve as a voltage standard, and this might well be a reputable testmeter which has a large scale conveniently calibrated in terms of 0-10 volts, with a d.c. sensitivity of not less than 20,000 ohms per volt. Even if the testmeter has an error of 2 per cent of the indicated reading on d.c. ranges, it should be capable of reproducing a given reading, from day to day under similar room temperature conditions, with much greater accuracy.

In addition to use as a voltage standard, the testmeter can, of course, be employed for setting up problems, answer readout, comparative resistance checks, and for general testing of all circuits. There is nothing to prevent re-calibration of the computer to laboratory voltage standards at a later date, and this has been allowed for in the overall design of PEAC.

## COMPUTER INSTRUMENTATION

Analogue computer instrumentation has much in common with electronic workshop equipment. Among those instruments likely to be of use to the computer operator are: an oscilloscope, a small collection of d.c. voltmeters, an audio oscillator, an a.c. voltmeter, and a component measuring bridge.

The oscilloscope need not conform to a modern specification, and could be a government surplus item. However, it is often an advantage to have a large screen area, and redundant television sets can be converted for computer readout purposes with excellent results. The limited bandwidth of magnetic deflection is no disadvantage at normal computer operating speeds.

D.C. voltmeters with centre zero scales are very useful for rough checks on the terms of a computer equation, where, for example, the wish is to see how  $y$  varies in relation to  $x$  when manipulating a simultaneous equation.

A sine wave oscillator, with attendant a.c. voltmeter, will often be employed for work on transfer functions, and for general electronic circuit simulation.

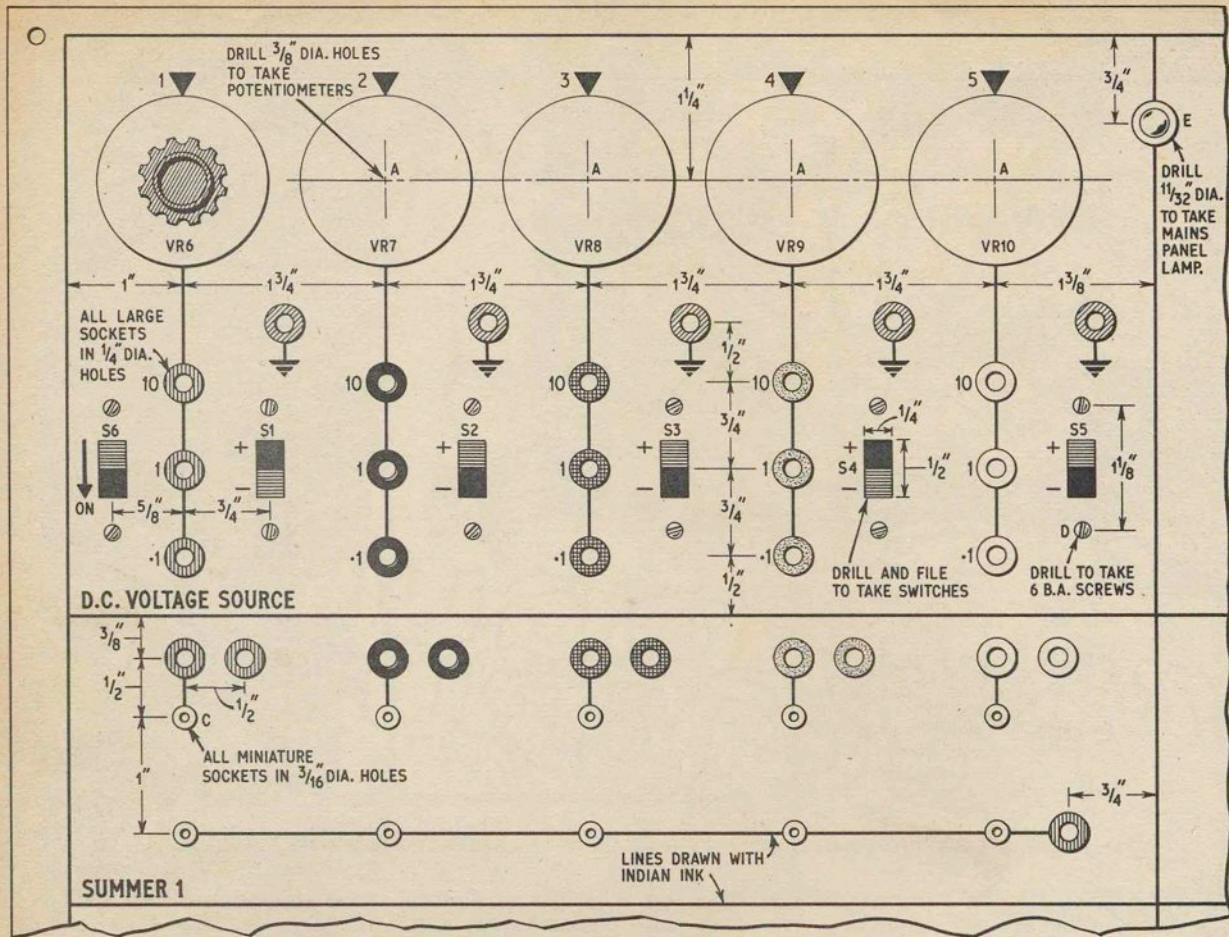
Finally, the component bridge is a help when making-up plug-in computing components, and for locating possible sources of error.

It is assumed that special classes of equipment, such as the XY plotter, will not be available to the amateur, and they are therefore excluded from further mention.

## UNIT "A" CONSTRUCTION

The general form of construction adopted for PEAC is based on a series of boxes made with laminates of white Armaboard or Formica and hardboard. The resulting box is rigid and durable, with a surface which easily takes panel transfers and lines drawn in Indian ink. With such a construction, it is possible to achieve a professional appearance using only simple woodworking tools.

It is advisable to start with the UNIT "A" front panel and case. This slightly unusual procedure, of building the box before starting on internal circuits,



● BLACK    ● RED    ● BLUE  
 ○ WHITE    ○ YELLOW    ○ GREEN

Fig. 2.2. Left-hand portion of front panel. Drilling details, layout of components, and panel engraving. (Below the broken line, there are two further sections, each a replica of "Summer 1")

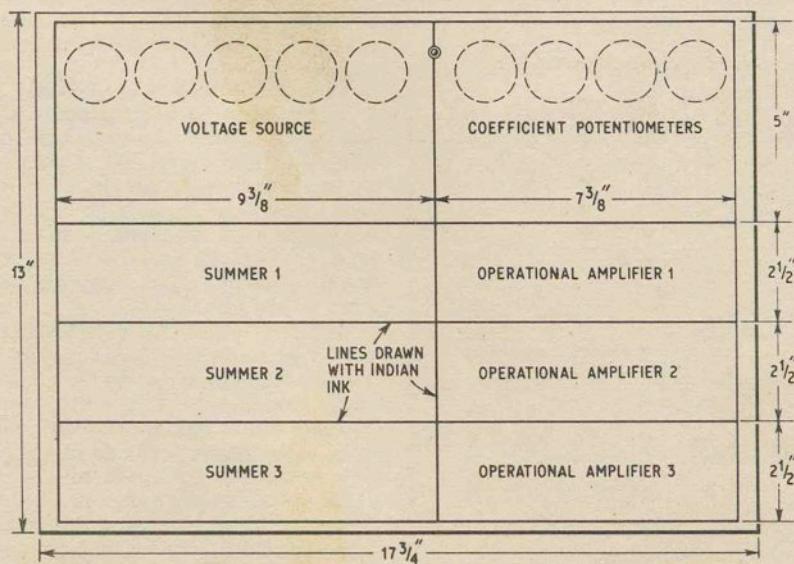


Fig. 2.1. UNIT "A" front panel. Overall dimensions and sectional dividing lines

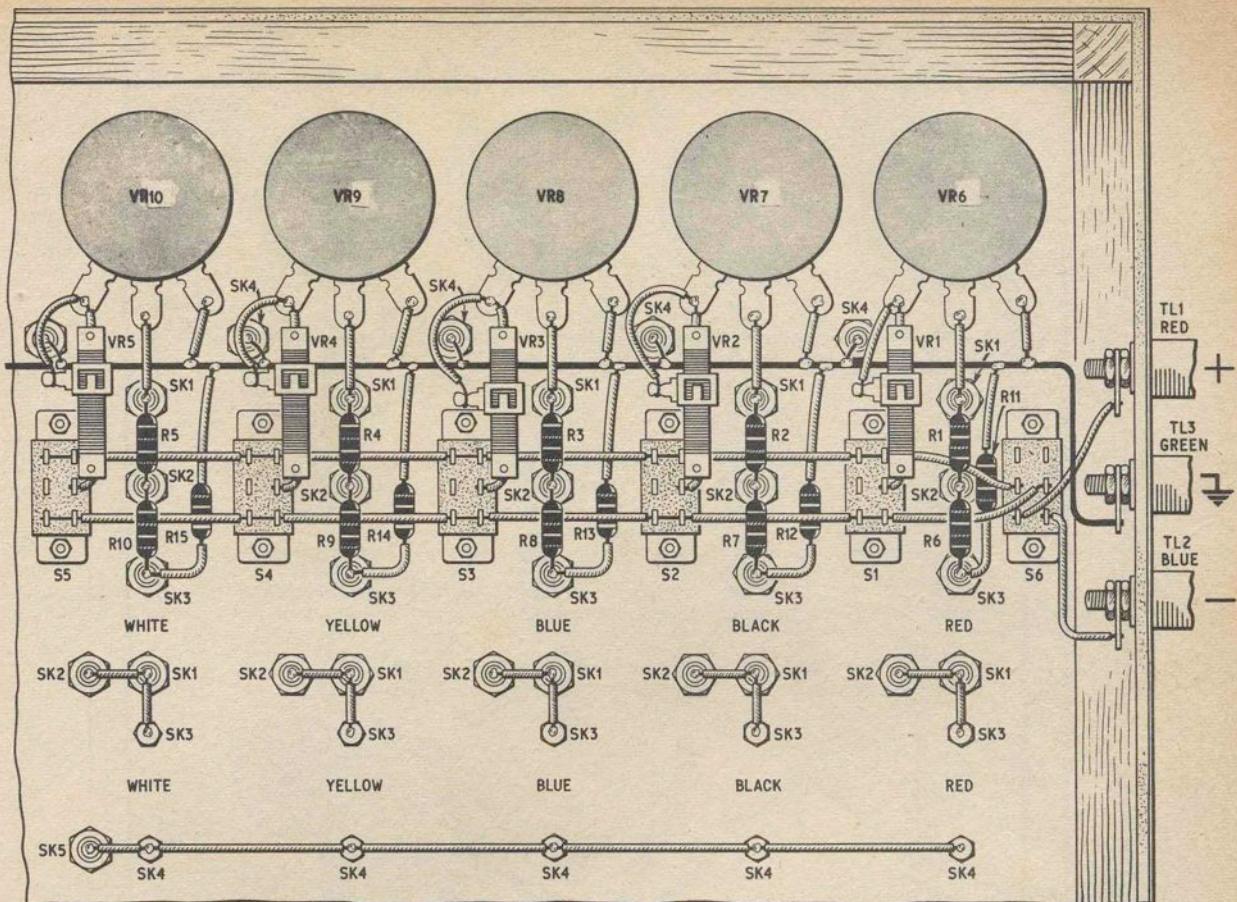


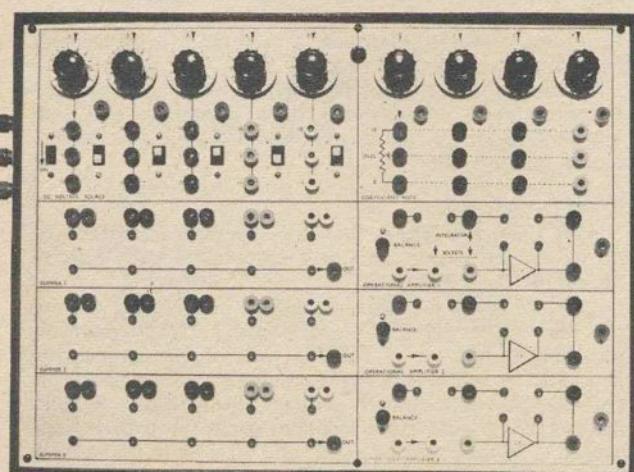
Fig. 2.3. Reverse side of front panel, left-hand portion (Fig. 2.2), showing components and wiring. Summer 2 and 3 are wired exactly as Summer 1 shown here. The three terminals TLI, 2 and 3 are mounted on the side of the box

may be justified on two counts: firstly, the front panel really forms a circuit which is designed to be accessible, and is an important part of the unit; secondly, the method of construction chosen brings economy by dispensing with a self-supporting internal chassis assembly, and much of the internal gear is actually mounted on the front panel, or to the box itself.

#### UNIT "A" FRONT PANEL

To prepare the front panel, a sheet of white plastic laminate, slightly larger than its finished size of 13in × 17½in, is glued to a sheet of hardboard of the same measurements with Evostick or a similar adhesive. When firm, the panel edges can be planed, rasped, or sandpapered down to size, while making sure that all is square. Next, taking Fig. 2.1 and the photograph of the front panel as a guide, mark out the main dividing lines with a pencil.

The positions of all holes and slots may be found by referring to panel drawings Fig. 2.2 and Fig. 2.5. Establish hole centres by first marking with a pencil, then indenting with a sharp spike. Note that all drilling should be carried out from the plastic laminate side of the panel, to avoid chipping the white surface. It is important to handle tools carefully, and prevent them skidding across the plastic surface and scoring it. When all holes have been drilled, deburr them on the reverse side of the panel with sandpaper, and check that components will fit correctly before applying a coat of clear varnish to the hardboard backing.



UNIT "A" front panel

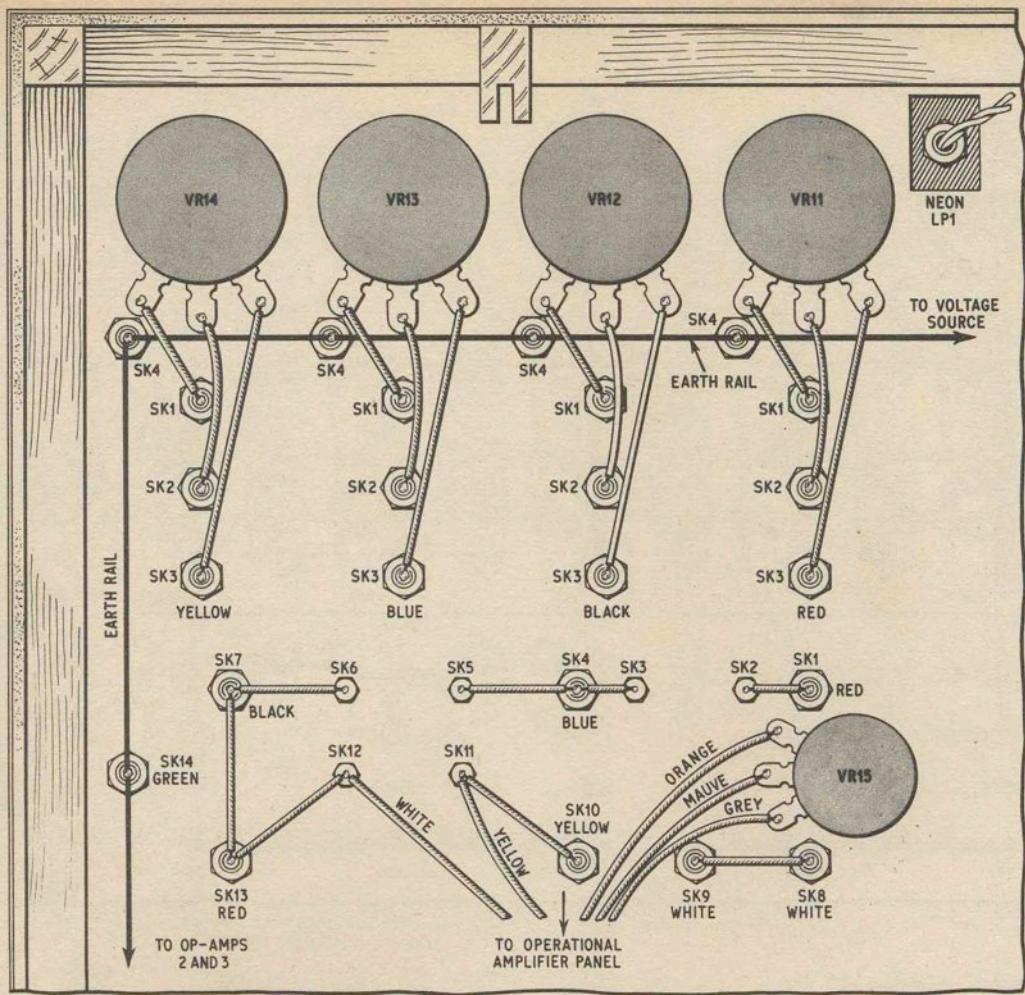
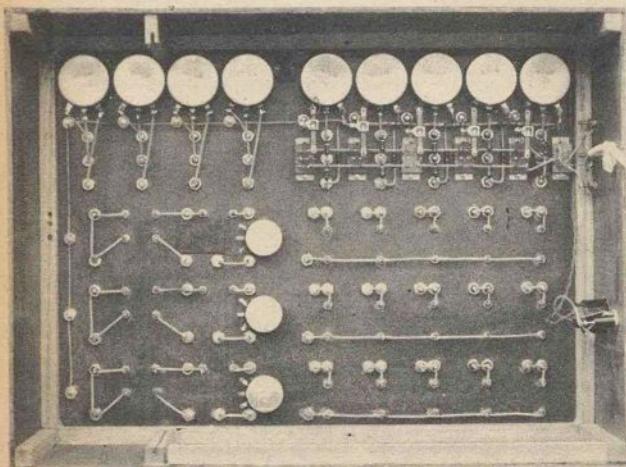


Fig. 2.4. Right-hand portion of front panel viewed from rear, showing components and wiring. Operational Amplifiers 2 and 3 are wired exactly as "Operational Amplifier 1" shown here.



Rear view of UNIT "A" front panel

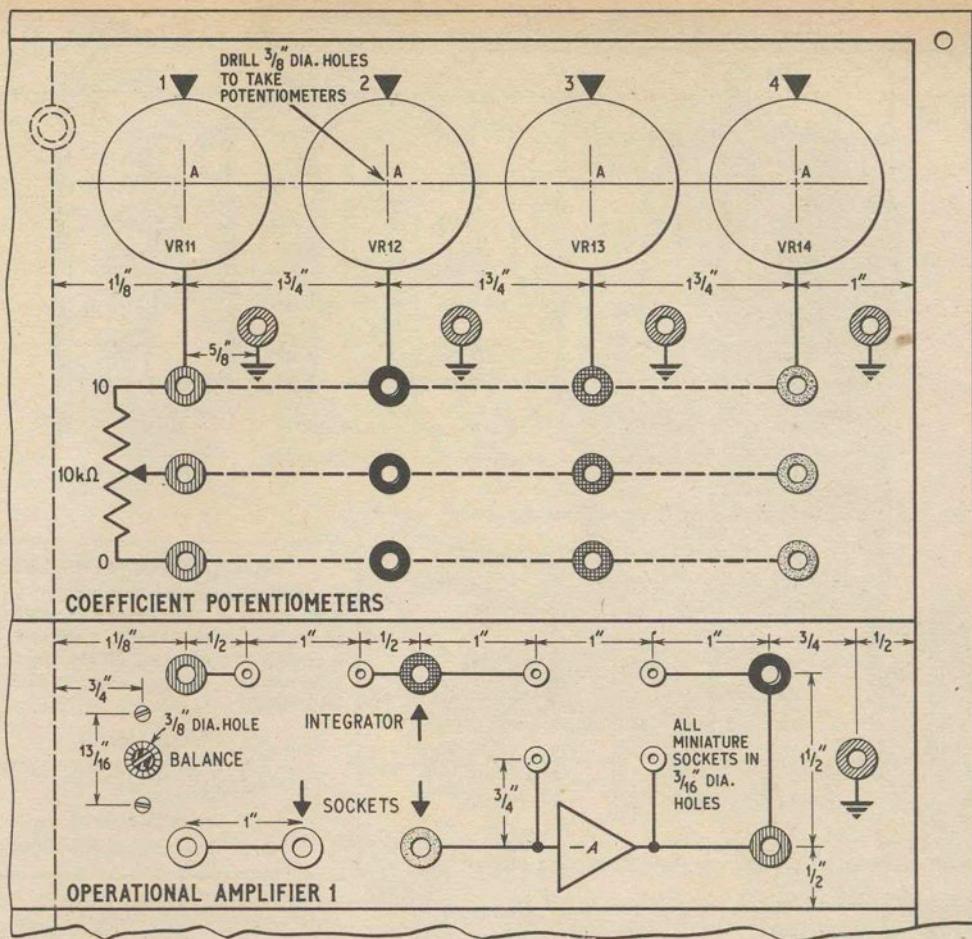
To finish the panel, draw in all lines and symbols with a nib pen and Indian ink. If any mistakes are made, the ink can be removed—when dry—with a typewriter eraser, and surface shine restored with metal polish. Lettering can be applied by the "rub-on" or "stick-on" transfer methods, and should be protected by a thin layer of clear varnish.

When the panel decor has dried, mount all sockets, potentiometers, knobs with dials, switches, and the neon mains lamp. Dials may be lined up on potentiometer spindles later.

#### UNIT "A" BOX

This time, the box is first constructed of hardboard on a wooden frame, and is later covered with plastic laminate. See Fig. 2.12.

Cut and finish the four hardboard panels to size, and cut the various lengths of softwood. The manner of assembly could be as follows: attach wood lengths *A* and *C* to top and bottom panels with panel pins or countersunk woodscrews, gluing all joints. Attach lengths *B* to side panels, bring panels together and secure. Next, position *D*, *E*, and *F*. Note that there is no length *D* at the back portion of the top panel so the slotted amplifier mount *F* should be lined up vertically with its companion *E*. All drilling must be left until the plastic laminate is in place.



## COMPONENTS . . .

Fig. 2.5. Right-hand portion of front panel. Drilling details, layout of components, and panel engraving. Below the broken line there are two further sections, each a replica of "Operational Amplifier 1"

### UNIT "A" FRONT PANEL AND BOX

#### Resistors

R1-R5 9.1kΩ (5 off)  
 R6-R10 910Ω (5 off)  
 R11-R15 100Ω (5 off)  
 All 5%, 1/2W carbon film

#### Pre-set Potentiometers

VRI-VR5 250Ω miniature wirewound slider type (5 off)  
 VRI5-VR17 50Ω wirewound panel mounting type (3 off)

#### Potentiometers

VR6-VR10 1kΩ 3W linear wirewound, ±20% or better, 270° effective rotation (5 off)  
 VR11-VR14 10kΩ 3W linear wirewound, ±20% or better, 270° effective rotation (4 off)

#### Switches

S1-S6 Double-pole, on/off slide switch (Radiospares) (6 off)

#### Plug

PLI 3 way panel mounting mains plug and cable connector

#### Fuse

FS1 1.5A cartridge fuse and 20mm fuseholder

#### Lamp

LPI Neon indicator lamp (Radiospares "miniature 200-250V panel neon" with self-contained resistor)

#### Sockets

21 Red, 15 Black, 15 Blue, 15 Yellow, 15 White, 12 Green (painted green, see text)  
 48 miniature sockets, black or red to choice

#### Terminals

Insulated screw, to take 4mm stackable plugs (Radiospares). 1 Red, 1 Green, 1 Blue

#### Miscellaneous

Material for panel and box: Hardboard: 2 off 13in × 5in, 2 off 18in × 5in, 1 off 13in × 17 1/2in. White plastic laminate: 2 off 13in × 5in, 2 off 18in × 5in, 1 off 13in × 17 1/2in. Softwood: 52in × 1in square, 4in × 7/8in × 1in.  
 20 s.w.g. tinned copper wire. Insulated sleeving

#### Dials and knobs

Nine 0-10 270° dial knobs (Bulgin type K400), black or grey

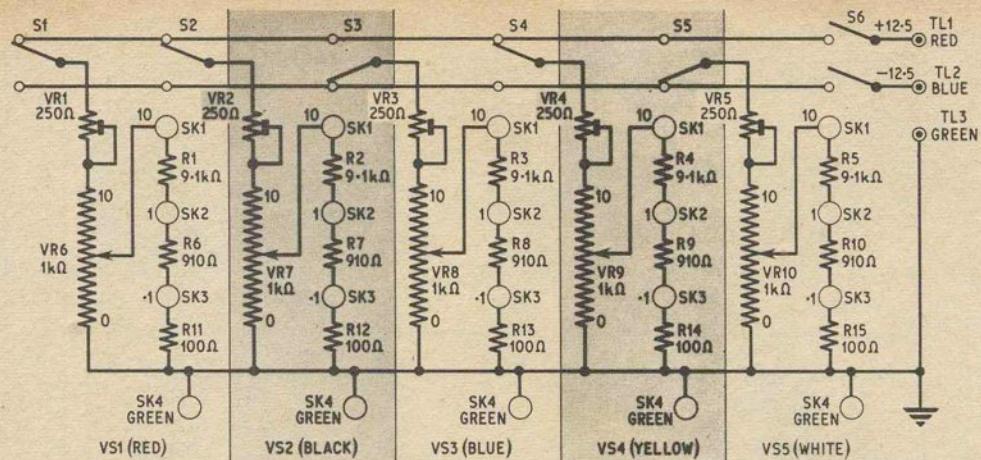


Fig. 2.6. Circuit diagram of Voltage Source section

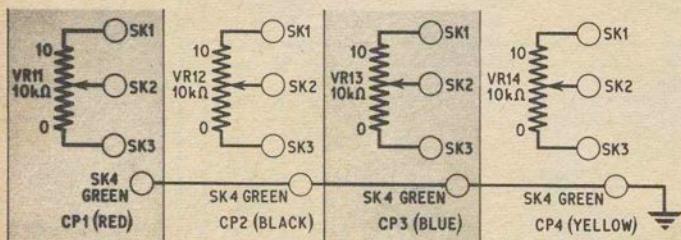


Fig. 2.7. Circuit diagram of Coefficient Potentiometers section

#### SOCKET IDENTIFICATION

The following abbreviations will be used in the programming instructions for PEAC. Applied as prefixes to socket (SK) numbers, they clearly establish the identity of the particular socket referred to. For example, "VS2/SK1"; "CP1/SK3" etc.

VS	Voltage source
CP	Coefficient potentiometers
S	Summer
I	Input (Summer)
OA	Operational Amplifier

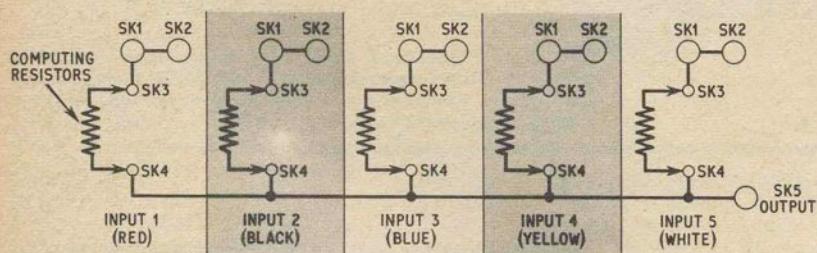


Fig. 2.8. Circuit diagram of Summer 1, 2, and 3

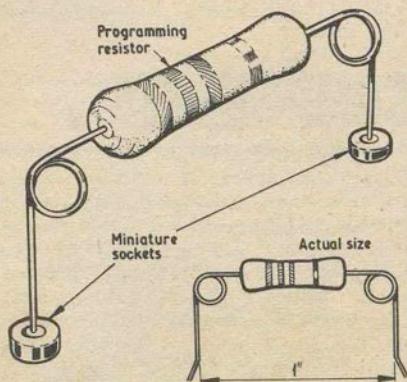


Fig. 2.11. Method of bending leads to make plug-in programming resistors

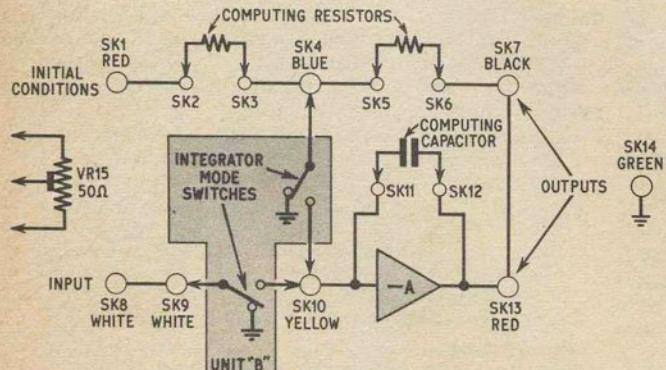


Fig. 2.9. Circuit diagram of Operational Amplifier 1, 2, and 3

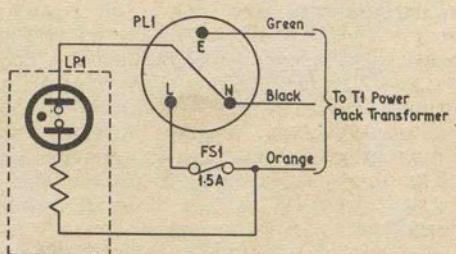


Fig. 2.10. Circuit diagram of mains supply

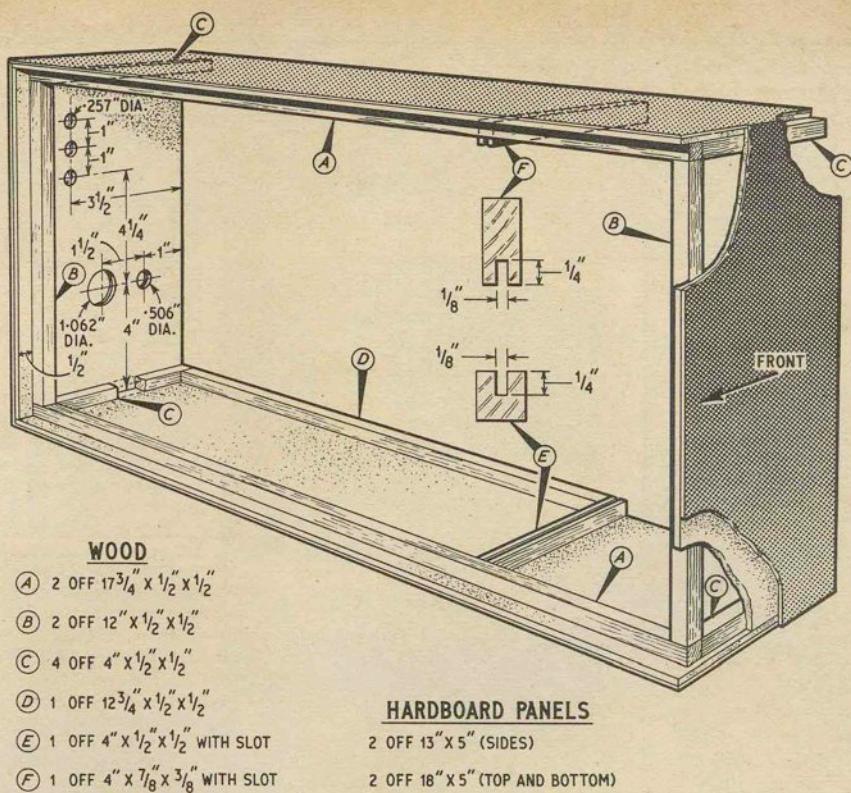


Fig. 2.12. Constructional details of UNIT "A" Box

Cut plastic laminate to fit hardboard panels with  $\frac{1}{8}$ in overlap, and glue to the box sides first. Reduce the overlap to size when the laminates are firm, before fitting the top and bottom surfaces. When trimming the top and bottom panels down to size, take care not to scratch and score the side pieces. For economy, the bottom plastic laminate layer can be omitted.

When satisfied with the laminated exterior, the 1.062in dia. hole can be made by a series of small drillings and finished with a half-round file. The box interior and wood may be varnished, but the raised lip at the front of the box is best painted black, or some dark colour, to contrast with the front panel.

The finished box is quite strong, and will support the full weight of a normal adult when the front panel is in place. However, it is recommended that this test should not be applied too often!

#### FRONT PANEL WIRING

Attach the front panel to its box, which will act as a convenient mount when wiring the back of the panel.

The bare earth wire linking all green sockets runs along the top half of the front panel and down its left-hand side, looking from the back; this should be soldered in place before embarking on the sleeved wiring. (No matching green sockets were available for the prototype, so odd coloured sockets were painted green with cellulose model aeroplane dope.)

The 4mm red, green, and blue terminal sockets on the side of UNIT "A" are designed to take stackable plugs, and will make available the power supply outputs to external sub-units. Wiring can proceed from the terminal sockets along the voltage source (see Fig. 2.3) and then to the rest of the front panel.

Circuit diagrams for all the various "sections" incorporated in the front panel are given in Figs. 2.6 to 2.10 inclusive. Wiring details are given in Fig. 2.3 and Fig. 2.4.

The summer and operational amplifier sections are triplicated—although only one of each of these sections has been shown in the diagrams Fig. 2.2 to Fig. 2.5 inclusive.

The purpose of the miniature sockets, which appear in the above mentioned diagrams, is to take the plug-in programming components; explained by Fig. 2.11. Resistor leads are preformed in the manner shown. The distance between miniature sockets is standardised at 1in, to allow the use of a special made-up two pin plug to support the bulkier components, such as large polyester capacitors.

When wiring up the operational amplifier sockets, ignore for the time being the coloured flexible wires shown in Fig. 2.4 as these are the flying leads from the operational amplifier panel, and will be referred back to when the time comes to mount the amplifiers.

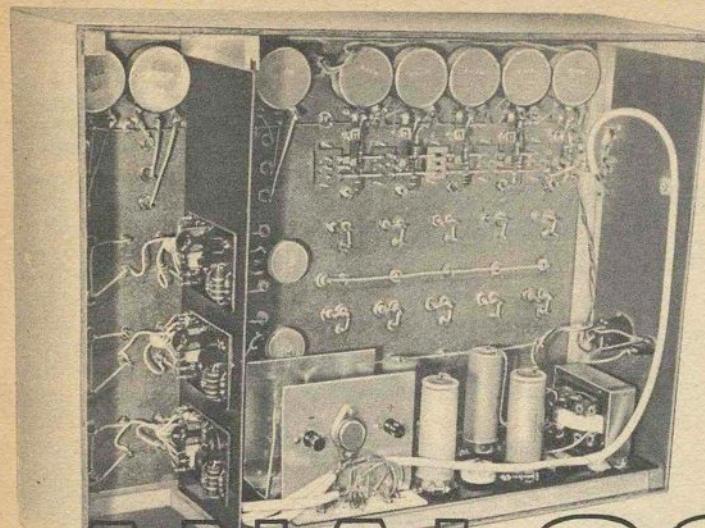
Fit the mains connector PL1 and fuseholder for FS1 to the side of the box. Wire up the neon lamp LPI and the fuse FS1 to PL1 as shown in Fig. 2.10.

#### CORRECTION.

In Part 1, Page 40, last line of the equation in the example at top of right-hand column should read:

$$E_0 = - \left( 5\frac{10}{10} - 3.5\frac{10}{2} + 2\frac{10}{100} \right) = - (5 - (3.5 \times 5) + 0.2), \\ \text{therefore } E_0 = 12.3.$$

**Next month: Power supply and operational amplifiers**



**PEAC**

By  
**D. BOLLEN**

# ANALOGUE COMPUTER

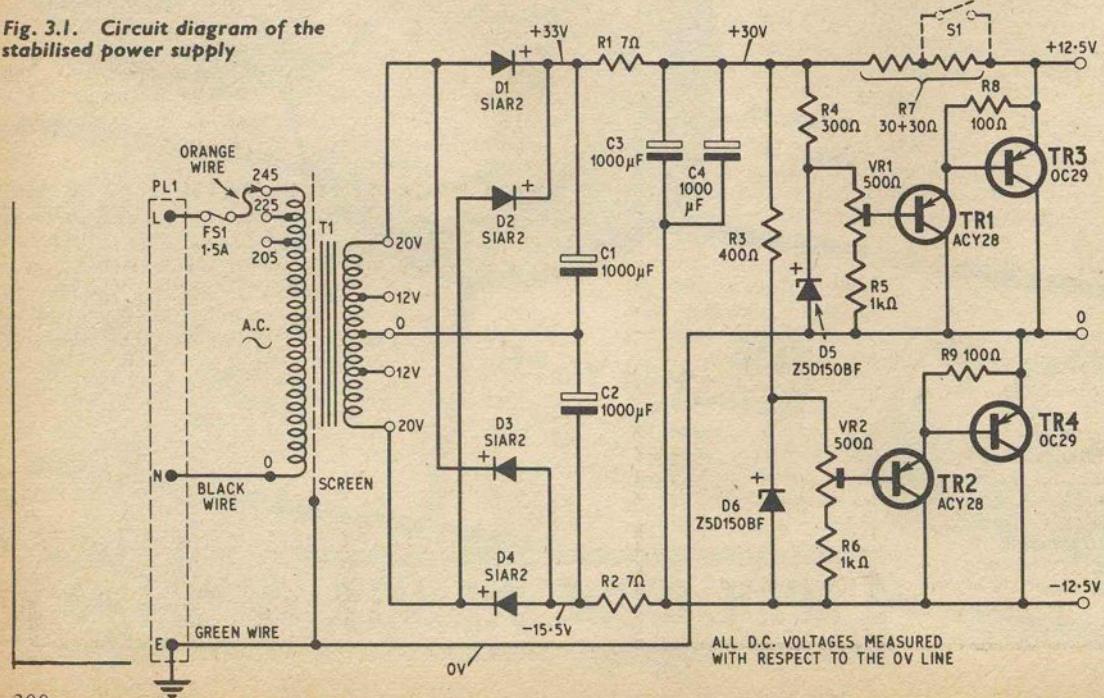
THE main design target for the PEAC power supply was a maximum voltage variation of not more than 1 per cent under all normal operating conditions. Several circuit configurations were tried, based upon either series or shunt regulation, but it was found that shunt regulation invariably gave the best performance for a given cost, plus the bonus of complete short-circuit protection. It was not considered to be a disadvantage for computer work, where nearly everything is switched on for most of the time, that a shunt regulated supply would be wasteful of power under no-load conditions.

The current reserve of the stabilised supply will just be sufficient to cater for the needs of UNITS "A to D". If further expansion of the computer is contemplated, beyond the inclusion of UNIT "D", a subsidiary unstabilised supply can be added to the computer at a late stage of construction, to power the relays of UNITS "B" and "D", and thus make available some extra current from the stabilised supply.

## STABILISED POWER PACK

The circuit of Fig. 3.1 is based on a small, standard type of rectifier transformer, with bridge rectification

Fig. 3.1. Circuit diagram of the stabilised power supply



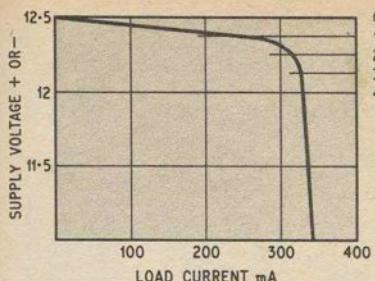


Fig. 3.2. Performance curve of stabilised power supply

followed by two shunt regulators arranged in series to give positive and negative outputs relative to a zero voltage earthed centre-tap. Diodes D1-D4 provide full-wave rectification of the 40V r.m.s. nominal transformer output. Capacitors C1 and C2 are wired in series, with their common connection taken to the transformer centre-tap, and this doubles the capacitor voltage rating without the need for bleeder resistors. R1 and R2 achieve some measure of preliminary ripple smoothing while dropping the unregulated d.c. voltage to a safe value for C3 and C4.

## COMPONENTS . . .

### UNIT "A" POWER PACK

#### Resistors

- R1, R2 7Ω 0.7A power resistors 5% (2 off)
- R3 400Ω 5W wirewound 5%
- R4 300Ω 5W wirewound 5%
- R5, R6 1kΩ 2W carbon 10% (2 off)
- R7 60Ω 0.7A power resistor 5% (two 30Ω in series, see text)
- R8, R9 100Ω 1W carbon 10% (2 off)

#### Potentiometers

- VR1, VR2 500Ω 3W panel mounting, wirewound (2 off)

#### Capacitors

- C1-C4 1,000μF elect. 50V d.c. 900mA rippled (4 off)

#### Transformer

- T1 Rectifier transformer. Standard mains primary. Secondary, 20V-0-20V 0.7A (Radiospares)

#### Diodes

- D1-D4 SIAR2 (Westinghouse) or DD2026 (Lucas) (4 off)
- D5, D6 Z5D150BF (STC) or IS5015R (Texas) (see text) (2 off)

#### Transistors

- TR1, TR2 ACY28 (STC) or AC126 (Mullard) (2 off)
- TR3, TR4 OC29 or OC36 (Mullard) (2 off)

#### Miscellaneous

- Four capacitor clips to fit C1-C4
- S.R.B.P. panel 4in × 12in ×  $\frac{1}{16}$ in or  $\frac{1}{8}$ in
- 4 B.A. and 6 B.A. assorted screws, nuts, washers, and solder tags
- Insulated sleeving
- 20 s.w.g. tinned copper wire
- 16 s.w.g. sheet aluminium 2 off 4in × 4in, and 2 off  $1\frac{1}{2}$ in ×  $1\frac{3}{4}$ in

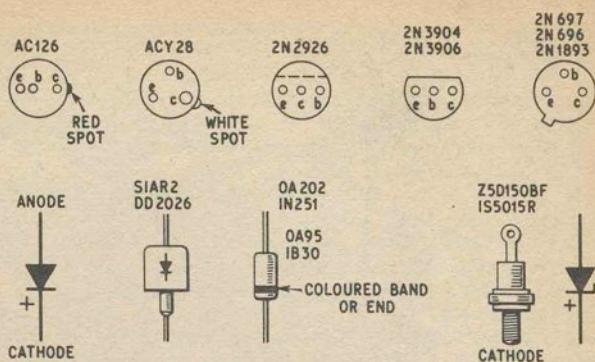


Fig. 3.3. Transistor and diode key

## SHUNT REGULATORS

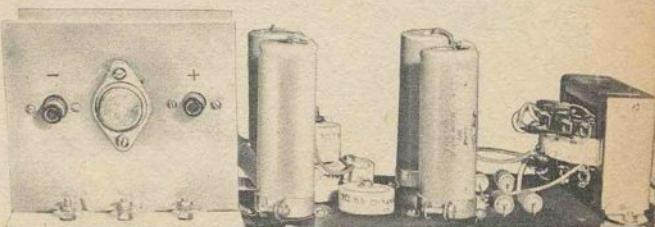
To understand the action of the twin shunt regulators, temporarily assume that the -12.5V output terminal is at zero voltage. The centre-tap and the positive outputs will then be positive in relation to the negative output. TR3 and TR4 collector-emitter voltages are both clamped at 12.5V, and the unregulated d.c. voltage is dropped across R7. Therefore, the voltage appearing at the junction of R7 and TR3 emitter is +25V relative to the assumed zero rail, with the centre-tap output at +12.5V. As all three output terminals are floating, it is a simple matter to connect the centre-tap output to an external earth and classify it as the zero voltage rail, with the other terminals forming positive and negative regulated outputs.

VR1 setting will determine the voltage across TR3, and VR2 the voltage across TR4. The range of adjustment of VR1 and VR2 is sufficient to allow for regulator diode (D5 and D6) tolerances on nominal voltage of ±15 per cent, and will therefore permit the use of manufacturers' rejects or "bargain" price regulator diodes. 10W diodes are specified for D5 and D6 in the Fig. 3.1 circuit, to achieve a low dynamic resistance, and reduce the short-term thermal changes which are inevitable when smaller regulator diodes are run at high temperatures.

Fig. 3.2 will give an idea of the capabilities of the regulated power supply, and maximum current limits. If an optional press-button switch is wired across one half of R7 (Fig. 3.1) output current can almost be doubled for short periods, and special purposes. The prolonged use of this extra current facility will, however, result in mains transformer overheating.

## POWER PACK CONSTRUCTION

Low cost semiconductors were used throughout the prototype power pack. The diodes D1-D4 should have a p.i.v. rating of not less than 100V, and a maximum current rating of 1A or more. It is advisable to check all diodes with an ohmmeter, for high reverse resistance and correct polarity. The D5 and D6



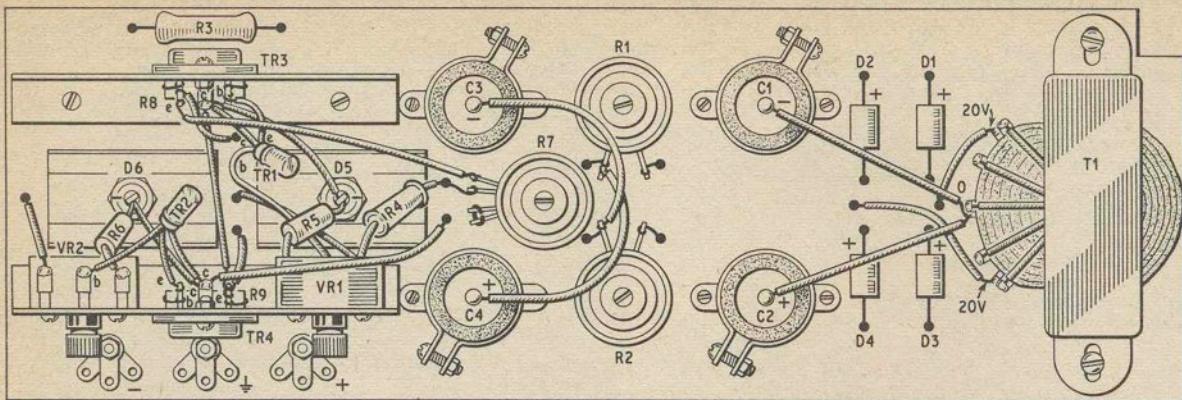


Fig. 3.4 Power supply component layout

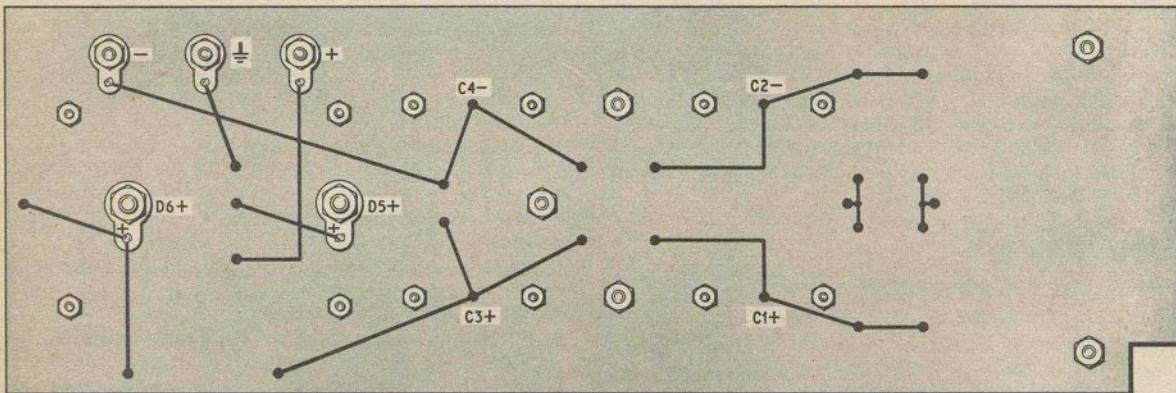


Fig. 3.5 Underside wiring of power supply panel

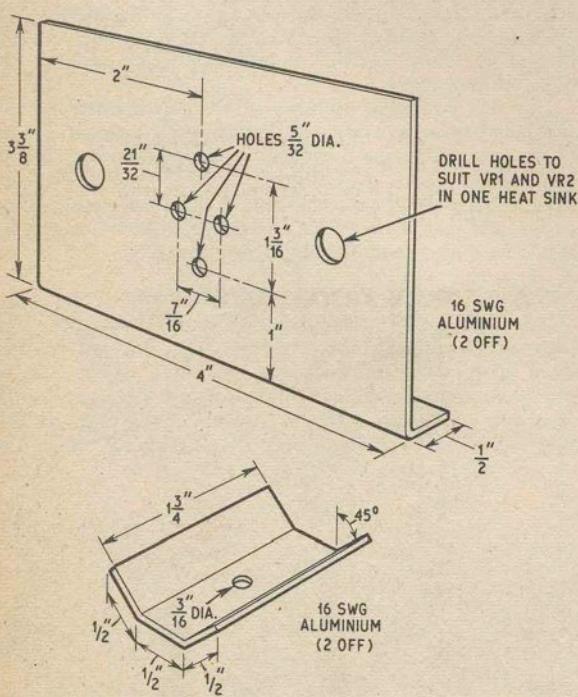


Fig. 3.6. Power supply heat sink details

measured voltage, when passing a current of about 100mA, can fall anywhere within the limits 12.5–17.5V.

If a choice exists, TR1–TR4 can be selected for highest beta gain, but matching is not necessary. Collector-emitter leakage currents of TR1 and TR2, with open circuit base, will preferably be below about 200 $\mu$ A at normal room temperature.

It is seriously recommended that the reader who intends to build PEAC should adhere closely to the semiconductor types specified here, and not consult other lists of equivalents. A key to transistor and diode connections appears in Fig. 3.3, and this covers all the semiconductors used in PEAC circuits.

Power pack components are assembled on a  $\frac{1}{8}$ in or  $\frac{1}{16}$ in s.r.b.p. panel measuring 4in  $\times$  12in. The panel sits on the wooden framework at the bottom of the UNIT "A" box. Component layout appears in Fig. 3.4, with the underside wiring in Fig. 3.5. Heat sinks for TR3, TR4, D5, and D6 are made up from 16 s.w.g. aluminium sheet, and measurements are given in Fig. 3.6.

First drill the s.r.b.p. chassis panel to accept hardware and wires, using Fig. 3.5 as a guide. Mount the mains transformer, capacitor clips, power resistors, and the three output terminal screws. Attach the regulator diodes, with their heat sinks and solder tags, to the panel, taking care not to damage the diode top terminals. Bolt TR4, VR1, and VR2 to the appropriate heat sink, solder R9 to TR4 emitter and base pins, and install the assembly on the s.r.b.p. panel. Similarly, bolt TR3 to its heat sink, complete with R8, and fix to panel.

Both power transistors should have a solder tag attached to their upper mounting bolts to make convenient connection to transistor collectors. Without insulating washers, TR3 and TR4 heat sinks will be "live", but damage is unlikely to result in the event of an accidental short-circuit.

Insert capacitors C1-C4 in clips, with polarity as indicated on Fig. 3.4. Also observe correct polarity when mounting diodes D1-D4. Before wiring up all components, insert R3 in the panel, alongside TR3 heat-sink.

#### COLOUR CODED WIRE

Wiring can start at the input end of the panel, with 6in lengths of orange, black, and green multi-stranded wire soldered to the live, neutral, and screen tags on the mains transformer. Red and blue wires are reserved exclusively for 12.5V d.c. positive and negative supply rails, with green wiring as the common earth throughout the computer.

Wire colour coding is almost essential for computer circuit interconnection, as it enormously simplifies fault tracing and assembly. However, the wiring of individual circuits, such as the power pack panel, can take the form of single colour sleeved 20 s.w.g. tinned copper wire.

It will be noticed (Fig. 3.4) that TR1 and TR2 are supported only by their leads, and this is to allow best positioning for good ventilation, well away from heat sinks. In the prototype R7 was made up from two 0.7A power resistor sections, to allow for the optional extra current facility mentioned earlier.

When power pack wiring is completed and checked, multiple solder tags can be fitted to the three output terminal screws.

#### TESTING THE POWER PACK

Connect the transformer input leads to the mains socket on the side panel of the UNIT "A" box, with the orange lead taken via FS1 (see Fig. 2.10 and Fig. 3.1), and, also join the neon indicator leads to the live and neutral mains socket screws.

Turn VR1 and VR2 fully anticlockwise and switch on. A quick check with a voltmeter will show if there is any serious departure from the voltages shown in Fig. 3.1. If any overheating of heat sinks or mains transformer seems imminent, switch off immediately and locate fault.

To set up the power pack, apply voltmeter leads to earth and positive output terminal, and advance VR1 for a reading of 12.5V. Repeat the procedure for the negative output and VR2. If it is impossible to bring an output to 12.5V, this will indicate a wiring fault or trouble with a regulator diode.

After the power pack has been left on for some time, VR1 and VR2 can be finally trimmed for exact outputs of  $\pm 12.5V$ . With no external load on the power supply, TR3 and TR4 heat sinks can be expected to run fairly warm.

To ensure that power pack regulation conforms to the curve of Fig. 3.2, positive and negative outputs can be loaded by a selection of 5W resistors in series with an ammeter, while voltage is still being monitored. A worst case variation of 2 per cent change in voltage for 300mA change in current should be taken as an acceptable performance limit. When one half of R7 is temporarily shorted out, at least 50 per cent more current should be available before voltage drops beyond 2 per cent.

Locate the power pack inside the UNIT "A" box, and wire outputs to the main terminals TL1, TL2, and TL3. Voltage source dial alignment and setting up details will be discussed later, but a few rough checks with power on are in order, to see that all voltage source sockets and switches are functioning correctly.

#### OPERATIONAL AMPLIFIER

The most important analogue computing circuit is the operational amplifier; so named because it will perform a number of mathematical operations, such as addition, subtraction, change of sign, multiplication by a constant, division by a constant, and integration. All the thinking behind "op-amp" design is concerned with making the circuit as unobtrusive as possible, so that it can be regarded purely as an operational "black box".

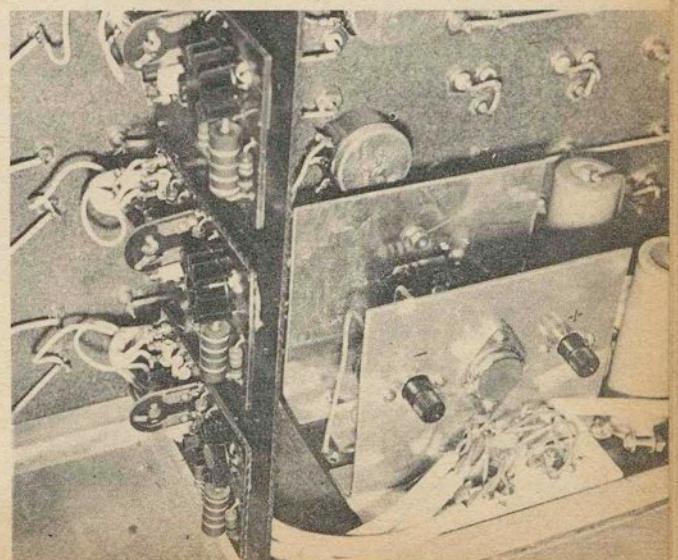
An analogue computer d.c. operational amplifier should comply with the following general requirements.

- (a) Direct coupling between all stages to handle d.c. signals. Input and output terminals at earth potential in the absence of a signal, with 180 degree phase change (inversion) between input and output. Output voltage swings both positive and negative in relation to earth, and as large as the computer reference voltage ( $\pm 10V$ ).
- (b) Large voltage gain in the open-loop configuration.
- (c) Low output impedance.
- (d) High input impedance.
- (e) Very low input current.
- (f) Sufficient bandwidth to cause negligible phase shift or attenuation of a signal up to the highest frequencies encountered.
- (g) Insignificant output voltage drift over several hours.
- (h) Good margin of stability when subjected to a wide range of different input, output, and feedback conditions.

Performance figures for UNIT "A" operational amplifiers are given in the Table 3.1, but to fully understand how some of the design problems are solved it is necessary to consult the actual "op-amp" circuit of Fig. 3.7.

#### OPERATIONAL AMPLIFIER CIRCUIT

The input stage of circuit Fig. 3.7 consists of a long-tailed pair (TR1, TR2), offering the advantages of high voltage gain, near zero input offset voltage relative to



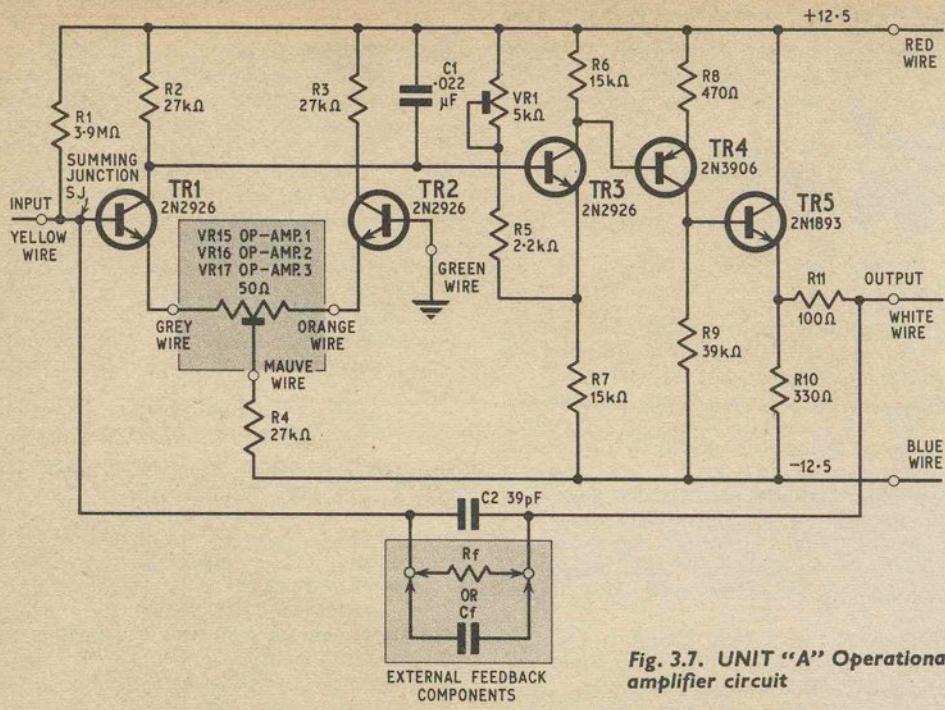


Fig. 3.7. UNIT "A" Operational amplifier circuit

## COMPONENTS . . .

### UNIT "A" OPERATIONAL AMPLIFIER

The following items are for a single amplifier, and are required in triplicate to cover the three amplifiers employed in UNIT "A".

#### Resistors

R1 3.9MΩ 5% carbon film  
 R2-R4 27kΩ 5% carbon film (3 off)  
 R5 2.2kΩ  
 R6, R7 15kΩ (2 off)  
 R8 470Ω  
 R9 39kΩ  
 R10 330Ω 2W  
 R11 100Ω  
 All ±10%, ½W carbon composition, except where otherwise stated

#### Potentiometer

VR1 5kΩ vertical skeleton pre-set

#### Capacitors

C1 0.022μF miniature polyester 250V d.c.  
 C2 39pF polystyrene 125V d.c.

#### Transistors

TR1-TR3 2N2926 orange (General Electric) or 2N3904 (Motorola) (3 off)  
 TR4 2N3906 (Motorola)  
 TR5 2N1893 (Bentron), 2N696, or 2N697 (General Electric).

#### Miscellaneous

S.r.b.p. panel 2in × 2½in  
 Eight small turret tags  
 TO-5 transistor cooler Type BC105B (Bentron)  
 6 B.A. screws, nuts, and spacers  
 Stranded core p.v.c. wires; red, green, blue, orange, mauve, grey, yellow, and white  
 12in × 4in s.r.b.p. amplifier mount  
 Note: All transistors and cooler can be obtained from Rastra Electronics Ltd., 275-281 King Street, Hammersmith, W.6.

earth, and low drift with change in temperature when TR1 and TR2 are closely matched. The long-tailed pair also gives good rejection of drift induced by changes in supply voltage, and has a reasonably large input impedance at low collector current levels.

An input signal will undergo a phase change of 180 degrees between the base and collector of TR1, and the voltage datum level is shifted away from earth towards the positive rail voltage. Ignoring for the moment C1, the signal is passed straight to the base of TR3.

VR1, R5, and R7 form an adjustable potential divider across positive and negative supply rails, and the VR1 setting determines the working points of direct coupled stages TR3, TR4, and TR5. Front panel control VR15 sets the amplifier input at zero volts, while VR1 does the same for the output.

TR3, while contributing some voltage gain, also introduces another 180 degree change of phase, to bring the overall phase difference between the amplifier input and TR3 collector to zero. Obviously, the voltage at the collector of TR3 will be even closer to positive rail voltage than the collector of TR1, but this cumulative voltage shifting can be virtually eliminated by using a pnp transistor for TR4. At the same time, TR4 common emitter stage brings more voltage gain and another and final phase change of 180 degrees.

So, the situation at the collector of TR4, when VR15 and VR1 are at correct settings, will be no overall voltage shift, a total phase difference of 180 degrees, and a total voltage gain in the region of 5,000.

Finally, the addition of an emitter follower stage provides the low input impedance required for driving a variety of useful loads, without unwanted circuit complications. TR5 causes negligible further voltage shifting, adds no change of phase, and with a voltage gain very close to unity, will simply reduce the output impedance of the operational amplifier without modifying its other characteristics.

## IMPORTANCE OF HIGH OPEN-LOOP GAIN

The ideal operational amplifier would have an infinite voltage gain when no feedback resistor was present, but since this is unattainable in practice, the effect of a finite open-loop gain on amplifier accuracy must be examined.

In Fig. 3.8, selected values of open-loop gain  $-A$  are plotted against closed-loop gains  $-G$ , and percentage amplifier error. Closed-loop gains are normally restricted to 0.1–50 as this caters for almost all operational conditions, and it is seldom required to extend these limits. A different set of circumstances apply when the op-amp is used for integration, and these will be considered in detail later.

Very high  $-A$  gains bring attendant drift and stability problems, and this in turn demands a larger number of components and more complicated circuitry to keep drift and stability within acceptable limits. At the opposite extreme, very simple amplifier circuits can

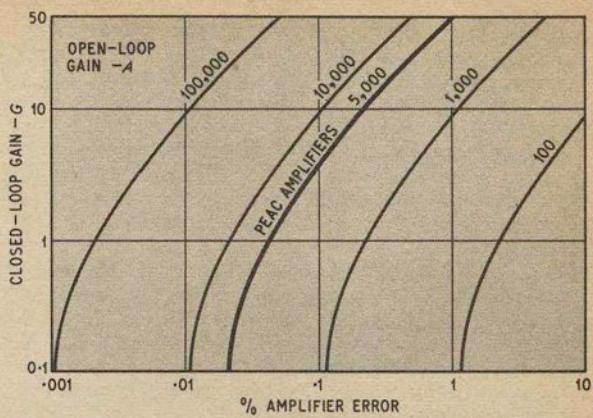


Fig. 3.8. Open-loop gain plotted against closed-loop gains and percentage amplifier error

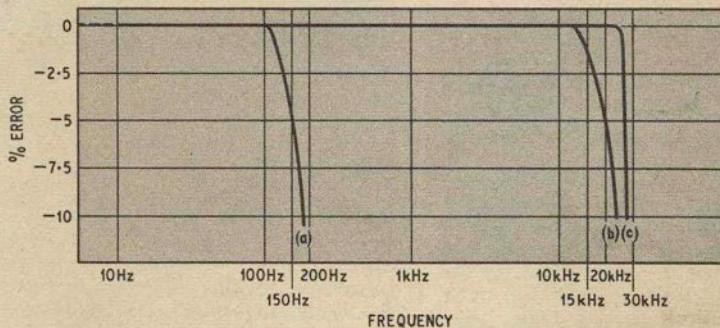
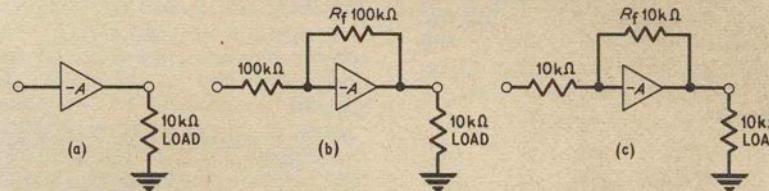


Fig. 3.9. Amplifier frequency response

TABLE 3.1

### UNIT "A" OPERATIONAL AMPLIFIER. TYPICAL PERFORMANCE

**Supply voltage**  $\pm 12.5V \pm 0.5\%$   
**Open-loop voltage gain** 5,000 d.c.—100Hz. 200 at 10kHz

**Maximum output voltage**  $\pm 10V$  for loads  $> 2k\Omega$   
 $\pm 5V$  for loads  $> 300\Omega$

**Input impedance**  $40k\Omega$  approx.

**Input current**  $0.005\mu A$  for 1V out

**Closed-loop frequency response** 0–10kHz within 1% when  $R_f = 100k\Omega$

**Equivalent input drift**  $\pm 0.5mV$  per hour

**Input offset voltage and current** almost zero when amplifier correctly balanced

**R.M.S. noise, referred to input with input open circuit**  $200\mu V$

**Normal maximum range of plug-in components**

$R_{in}$  2–100k $\Omega$

$R_f$  10–100k $\Omega$

$C_f$  1–0.01 $\mu F$

**Stability** unconditional with all normal problem layouts

be built to yield  $-A$  gains in the region of 100–1,000, but when  $-G$  approaches 50 the errors of such amplifiers would be near 10 per cent. Thus, if a low value for  $-A$  was chosen, for the sake of simplicity, the range of available closed-loop gains would have to be restricted if the error was not to exceed one or two per cent, and this would place severe limitations on the operational flexibility of the amplifier.

It was assumed that PEAC operators would not wish to employ plug-in computing components with a selection tolerance better than, say,  $\pm 1$  per cent. Therefore, the error contributed by the amplifier will preferably be less than external component errors, but not so small as to call for ridiculous extremes of circuit sophistication. The thickened curve of Fig. 3.8, corresponding to  $-A = 5,000$ , shows that the maximum error contribution of UNIT "A" amplifiers is 1 per cent or less for  $-G$  gains of less than 50.

### BANDWIDTH AND STABILITY

A direct coupled amplifier of the Fig. 3.7 type will display an almost constant phase change of exactly 180 degrees over a range of frequencies from d.c. to

about 20kHz. Thereafter, with increasing frequency, the phase angle will begin to shift until, at several hundred kHz, and especially when the amplifier has a high gain, sufficient positive feedback is present to cause sustained oscillation. To counteract this instability, small capacitors are suitably situated in the op-amp circuit to reduce gain at critical frequencies, and it follows that the use of such capacitors will place a limitation on the available frequency response of the amplifier.

$C_1$  of Fig. 3.7 will block the unwanted high frequency content of incoming signals, and plays a major role in determining the bandwidth of the amplifier. If  $C_1$  is reduced in value, bandwidth will be increased, but so will the likelihood of instability. Needless to say, any form of instability will be highly detrimental to accuracy, and must be avoided at all costs.  $C_2$  works in a different way, by introducing negative feedback and consequent loss of gain at very high frequencies. Both capacitors act together to combat instability under the very varied conditions of operational amplifier use.

The measured frequency response of a representative UNIT "A" amplifier is given in Fig. 3.9, and is very linear up to the well-defined break frequencies of (a) open-loop, (b) with feedback resistor of 100 kilohm, and (c) when  $R_f = 10$  kilohm.

#### DRIFT

If a d.c. amplifier is adjusted so that its output voltage is zero when there is no input signal, over an interval of minutes, hours, or days—depending on the amplifier, its power supply, and its surroundings—a spurious voltage will begin to appear at the output. A poor amplifier in adverse conditions will require frequent manual adjustments to keep its output at zero. Fortunately, drift errors are very small when an operational amplifier is used for summing and sign changing, due to the presence of a feedback resistor, and no adjustment of the amplifier will be called for during intervals of perhaps several hours, except in applications requiring a very high degree of accuracy. However, when the operational amplifier is being used as an integrator, with a capacitor in its feedback loop, it is quite possible for drift errors to exceed 1 per cent within a space of less than an hour if suitable precautions are not taken.

The figure quoted in Table 3.1 for drift is the amount of input voltage, either positive or negative, required at the amplifier summing junction to reset the amplifier output to zero after it has been allowed to drift for one hour following a preliminary computer warm-up period. In practical terms, a drift of about  $\pm 0.5\text{mV}$

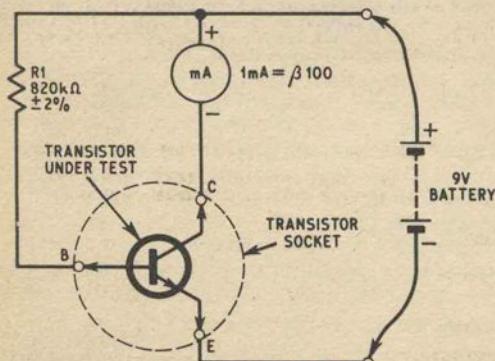
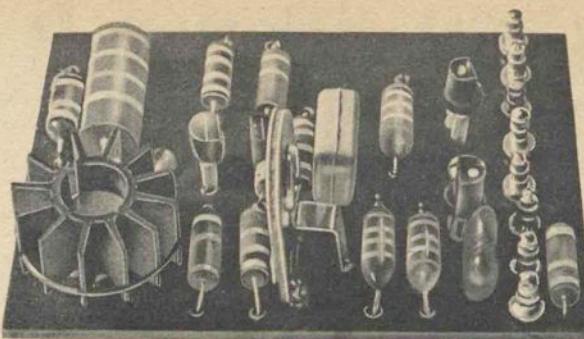


Fig. 3.10. Transistor test-rig. Note: reverse battery connections and milliammeter for pnp



per hour is not likely to prove to be too troublesome with most PEAC applications. Full scale analogue computers are sometimes installed in a temperature controlled computing room, and this considerably improves drift performance.

#### TRANSISTOR SELECTION

Several prototype UNIT "A" amplifiers were constructed using non-selected transistors, and about one third of the amplifiers failed to meet the specification of Table 3.1. Defects were due entirely to "spreads" in semiconductor characteristics, and disappointment will be avoided if all amplifier semiconductors are tested before use.

It has already been mentioned that the long-tailed pair input stage transistors (TR1 and TR2 in Fig. 3.7) should be matched. In all nine transistors of the same type will be required for TR1, TR2, and TR3 in the three operational amplifiers, and it will assist the matching and selection process if, say, one dozen transistors are purchased at the same time. No wastage will be involved as "spare" transistors can later be used up in other PEAC circuits.

A simple test-rig circuit is given in Fig. 3.10 to facilitate the matching of TR1 and TR2, and the circuit can also be quickly adapted for checking other transistors. The test-rig could take the form of a transistor socket and resistor mounted on an odd piece of s.r.b.p., or Veroboard, with a testmeter employed as a milliammeter.

Select each TR1–TR2 pair for near identical betas of 100 or more; this will dispose of six transistors. Do not attempt to pair off transistors of different types even if they do have the same beta. From the remaining transistors, choose three with the highest beta for TR3.

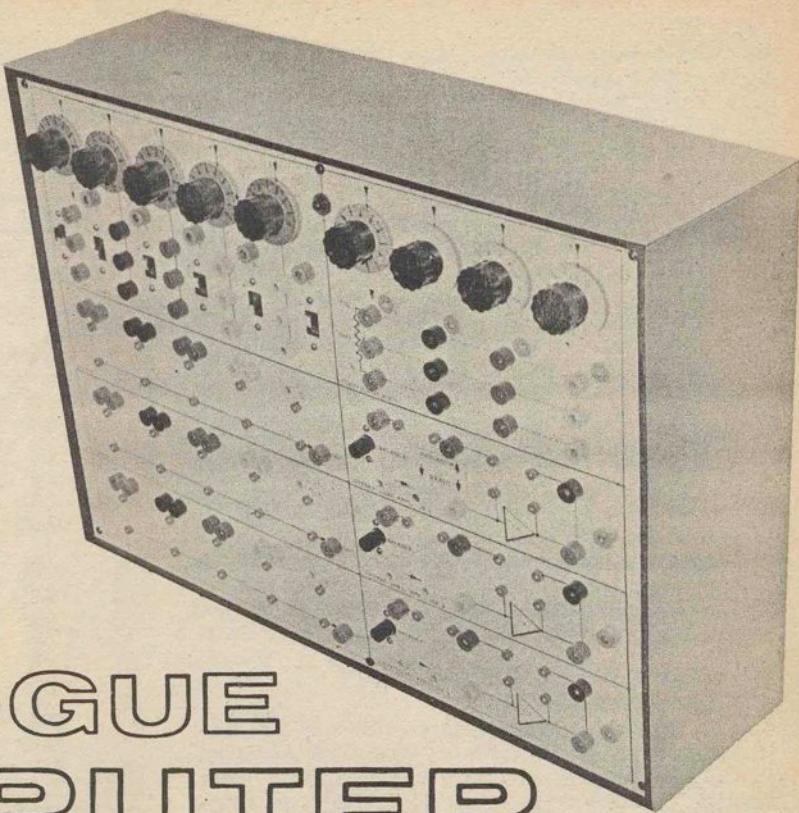
Although TR4 is a *pnp* transistor, it must be of silicon construction for low leakage drift. The majority of *pnp* silicon types at present on the market are unsatisfactory for use in the op-amp circuit because they exhibit almost no gain at all at very low collector current levels. Of all the types so far tested only the 2N3906 was found to be consistently good at low currents, therefore a suitable equivalent cannot be quoted. To check TR4, reverse the battery leads to the Fig. 3.10 test-rig, and switch connections to the milliammeter before plugging in the *pnp* transistor. TR4 should display a beta of about 50 or more.

When handling plastic encapsulated transistors, which tend to look alike, take note that lead connections do not necessarily conform to a common pattern. In particular, notice the lead differences between types 2N2926 and its equivalent 2N3904, and remember that the 2N3906 is *pnp*. To avoid mishaps, always refer to Fig. 3.3 before applying current to the transistor.

**By  
D. BOLLEN**

**PEAC**

# **ANALOGUE COMPUTER**



THE constructional details for UNIT "A" were completed last month. UNIT "A" is, itself, a complete, self-contained computing equipment, and the method of operation, with practical examples, is described in this article.

#### **PATCHING LEADS**

The best plugs to use for patching the computer are those of "split-pin" construction, as they can quickly be attached to wires without the aid of a screwdriver. It is a help if plugs are obtained in various colours, and are mated to different coloured wires to allow easy identification.

For the majority of problems capable of solution by UNIT "A", certain patching leads may be left in position on the front panel. For example, coefficient potentiometers are almost always used with the "0" end of their resistance track connected to earth (link SK3 to SK4 for CP1, CP2, CP3, and CP4, Fig. 2.7).

Similarly, until such time as integrator mode switching is brought into use, the integrator sockets depicted in Fig. 2.9 are joined together by means of a special three-way patching lead consisting of two short lengths of wire joined by a plug, with a plug at each end. Looking at Fig. 2.9, OA1/SK4, SK9, and SK10 are linked, and repeat for OA2 and OA3. Three more semi-permanent patching leads are made up to link each operational amplifier to its companion summer network. Connect OA1/SK8 to S1/SK5, and do the same for OA2/SK8-S2/SK5, and OA3/SK8-S3/SK5.

The rearrangeable patching leads should be of assorted lengths and colours, the longest to patch from, say, CP4/SK2 to S3/I1/SK1, diagonally across the UNIT "A" front panel, and the shortest to link nearly adjacent sockets.

#### **COMPUTING RESISTORS**

If a comprehensive range of  $\pm 1$  per cent high stability computing resistors was purchased all at once, to meet every requirement, the cost would probably exceed £20. There are after all 101 preferred values in a  $\pm 1$  per cent range covering resistors from only 10 kilohm to 100 kilohm. Nevertheless, in the period when the computer operator is learning how to handle PEAC, and a high degree of accuracy is not essential, the majority of ordinary problem set-ups can be catered for by a small number of  $\pm 1$  per cent and  $\pm 2$  per cent plug-in resistors. A resistor selection list, with suggested values of  $R_t$  and  $R_{in}$  for standard op-amp closed-loop gains, is given in Table 4.1. Also, a component list included in this article sets out minimum quantities, with tolerances, of computing resistors.

Computing capacitors will be discussed later, in connection with integration.

#### **SETTING UP THE VOLTAGE SOURCE**

To set up all voltage source outputs, first remove the diodes from VR6 to VR10 (Fig. 2.2), and turn the potentiometer spindles fully anticlockwise. If the potentiometers have flats on their spindles, make up blanking pieces consisting of small segments of hard-wood or plastic, so that control knobs can be conveniently located at a selected position on each spindle. Connect the positive lead of a sensitive d.c. voltmeter (0-1V, 20 kilohm/V) to VS1/SK1, and the negative voltmeter lead to VS1/SK4 (Fig. 2.6), then set slide switch S1 for a positive voltage output. Switch on the computer power supply and S6.

Carefully rotate VR6 spindle clockwise until a very small voltage appears, just sufficient to slightly deflect

the meter pointer away from zero. Now place a dial knob on VR6 spindle, without disturbing the potentiometer setting, and align so that the "0" division on the dial is vertical and opposite the pointer mark on the surface of the front panel. Tighten the dial knob grub screw.

Switch off S6 and replace the 0-1V meter with the 0-10V d.c. meter which has been chosen to serve as a voltage standard for the computer, while retaining the same meter lead polarity. Rotate VR6 dial until the "10" division is opposite its pointer, and switch on S6. Now adjust slider resistor VR1 from the back of the UNIT "A" box, for a precise reading of 10V on the "standard" meter. Repeat the above procedures for outputs VS2, VS3, VS4, and VS5, and remember to adjust only the particular slider (VR1-VR5) which is associated with the output being set up.

When all the voltage source dials are aligned, return to VS1 and make sure that its output is still +10V. Switch off S6, reverse the "standard" voltmeter leads, and set S1 for a negative output. Switch on S6 again and check the voltmeter reading; if it is not exactly 10V, go to the back of the UNIT "A" box and trim the power pack control VR2 (Fig. 3.4), this ensures that voltage source negative and positive outputs are equal.

#### SETTING UP THE COEFFICIENT POTENTIOMETERS

Insert a patching lead to link CP1/SK3 to CP1/SK4 (Fig. 2.7), and do the same for CP2, CP3, and CP4. Take a long patching lead from VS1/SK1 to CP1/SK1. Remove the dial from VR11 (Fig. 2.5) and rotate spindle fully clockwise. With the negative lead connected to any earth socket, insert the "standard" meter positive lead into CP1/SK2 after first setting S1 for a positive output. Adjust VS1 dial for a meter reading of 10V. Rotate CP1 spindle carefully anti-clockwise until the meter pointer just begins to drop below the 10V division. Replace CP1 dial knob on VR11 spindle, align the "10" division with the pointer, and tighten the grub screw. Repeat for CP2, CP3, CP4.

With a 10V input to CP1/SK1, and a 0-10V meter connected to CP1/SK2, it is a simple matter to check the agreement between dial divisions and voltage output from the coefficient potentiometer. If there are serious discrepancies between voltage output and dial reading this will indicate that the effective electrical rotation of the potentiometer differs from the 270 degree dial calibration. Errors can often be minimised by slight readjustment of the dial knob on its spindle, to spread the error over the entire scale. Generally

TABLE 4.1  
SUGGESTED VALUES OF COMPUTING RESISTOR FOR STANDARD CLOSED-LOOP GAINS

Op-amp gain	All resistors $\pm 2\%$ unless otherwise stated	
$\frac{R_f}{R_{in}} = -G$	$R_{in}$	$R_f$
0.1	100k $\Omega$	10k $\Omega$
0.2	100k $\Omega$	20k $\Omega$
0.3	33k $\Omega$	10k $\Omega$
0.4	40k $\Omega \pm 1\%$	10k $\Omega$
0.5	20k $\Omega$	10k $\Omega$
0.6	33k $\Omega$	20k $\Omega$
0.7	13k $\Omega$	9.1k $\Omega$
0.8	20k $\Omega$	16k $\Omega$
0.9	20k $\Omega$	18k $\Omega$
1.0	{ 100k $\Omega$	10k $\Omega$
2.0	10k $\Omega$	20k $\Omega$
3.0	{ 3.3k $\Omega$	10k $\Omega$
4.0	{ 40k $\Omega \pm 1\%$	100k $\Omega$
5.0	20k $\Omega$	100k $\Omega$
6.0	3.3k $\Omega$	20k $\Omega$
7.0	13k $\Omega$	91k $\Omega$
8.0	2k $\Omega$	16k $\Omega$
9.0	2k $\Omega$	18k $\Omega$
10.0	10k $\Omega$	100k $\Omega$
20.0	5k $\Omega \pm 1\%$	100k $\Omega$
30.0	3.3k $\Omega$	100k $\Omega$
40.0	4k $\Omega \pm 1\%$	100k $\Omega$
50.0	2k $\Omega$	100k $\Omega$

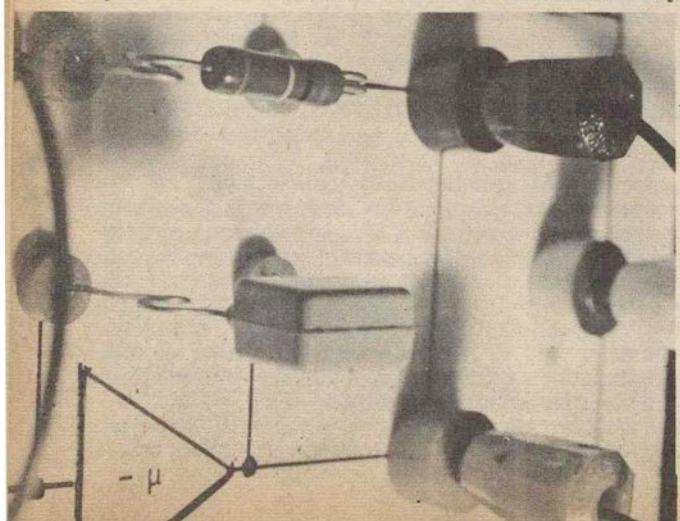
speaking, the dial setting error should not be worse than 5 per cent at all settings between "1" and "10" dial divisions. The whole question of computing potentiometer accuracy will be raised later, in connection with the Master Potentiometer of UNIT "B".

#### SETTING UP THE OPERATIONAL AMPLIFIERS

It is usual to check operational amplifiers either before the start of a computation, or at the beginning of the day, but the computer builder may wish to assure himself that his amplifiers are all that they should be when first brought into service. The zero-setting procedure given at the end of Part 3 of this series will have eliminated all but obscure faults. The front panel balance controls (VR15, VR16, and VR17, Figs. 2.4 and 2.9) are deliberately designed to have a limited range of adjustment, so that an amplifier fault will be clearly indicated as an inability to zero-set from the front panel.

To quickly check each amplifier, insert 10 kilohm feedback resistors into miniature sockets SK11 and SK12 for OA1, OA2, and OA3 (Fig. 2.9), and ensure that the operational amplifiers are already linked to their summing networks. Insert 10 kilohm input resistors into S1/I1/SK3-SK4, S2/I1/SK3-SK4, and S3/I1/SK3-SK4 (Fig. 2.8). Patch VS1/SK1 to S1/I1/SK1 (Figs. 2.6 and 2.8) and connect the negative lead of a voltmeter to OA1/SK13, with the positive lead going to any convenient earth socket.

Check that OA1 output is exactly zero when S6 is off. If not, zero-set by means of balance control VR15. Obtain a positive voltage from VS1 by switching on S6 and setting S1 and VR6, and monitor VS1 output with a second voltmeter connected to SN1/SK2 red, and an



# COMPONENTS . . .

## UNIT "A" COMPUTING RESISTORS AND PATCHING LEADS

### Resistors

- 3 off  $2\text{k}\Omega \pm 2\%$
- 3 off  $3\cdot3\text{k}\Omega \pm 2\%$
- 3 off  $4\text{k}\Omega \pm 1\%$
- 3 off  $5\text{k}\Omega \pm 1\%$
- 3 off  $9\cdot1\text{k}\Omega \pm 2\%$
- 5 off  $10\text{k}\Omega \pm 1\%$
- 5 off  $10\text{k}\Omega \pm 2\%$
- 3 off  $13\text{k}\Omega \pm 2\%$
- 3 off  $15\text{k}\Omega \pm 2\%$
- 3 off  $16\text{k}\Omega \pm 2\%$
- 3 off  $18\text{k}\Omega \pm 2\%$
- 3 off  $20\text{k}\Omega \pm 2\%$
- 3 off  $33\text{k}\Omega \pm 2\%$
- 3 off  $40\text{k}\Omega \pm 1\%$
- 3 off  $91\text{k}\Omega \pm 2\%$
- 5 off  $100\text{k}\Omega \pm 1\%$
- 5 off  $100\text{k}\Omega \pm 2\%$

(All metal oxide or carbon film, 1 W)

### Plugs

1 dozen of each colour: red, black, blue, yellow, and white, to fit front panel sockets (see text). 1 dozen miniature plugs, to fit miniature sockets

### Wire

Stranded core single p.v.c. wires in assorted colours (14·0076in).

**Fig. 4.1. (right)** These diagrams indicate how the operational amplifier can be used to solve various algebraic equations

earth socket. Remember that a positive input voltage results in a negative operational amplifier output voltage.

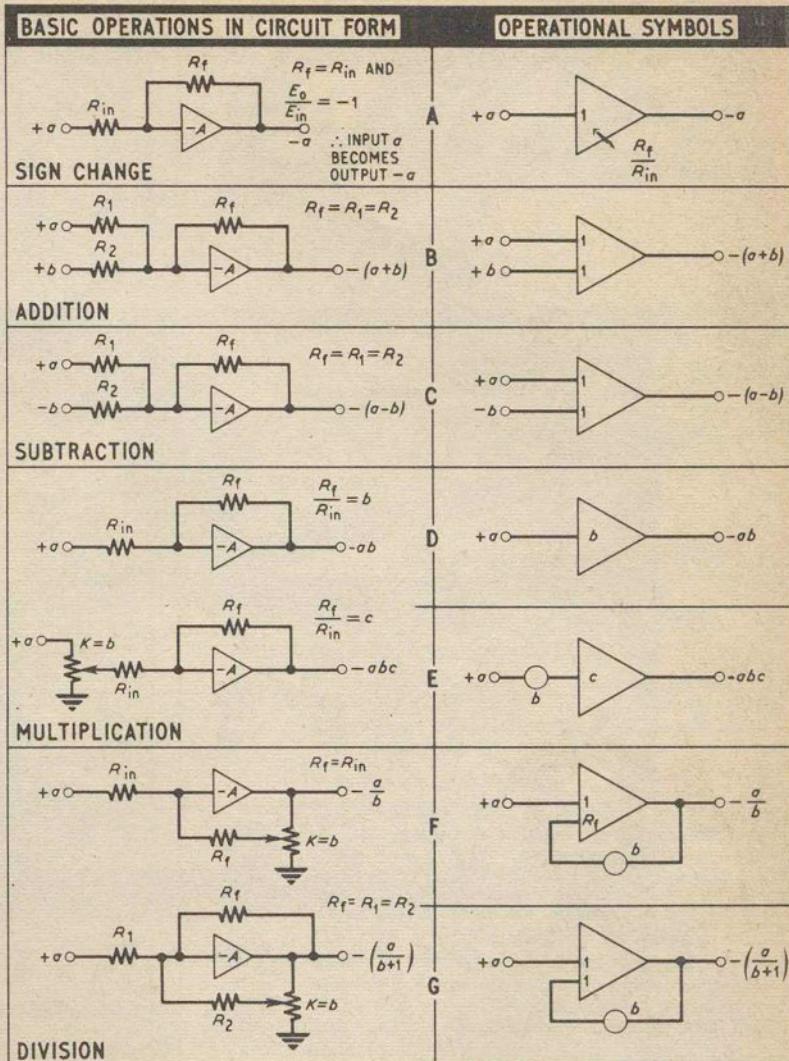
Since input and feedback resistors are both 10 kilohm, the operational amplifier gain will be unity, and both voltmeters should give precisely the same readings. Double check by interchanging voltmeters. Now see that the operational amplifier will faithfully "track" any input voltage of  $\pm 10\text{V}$  or less when a temporary output load of 2 kilohm is connected from OA1/SK7 to earth.

The above tests are repeated for OA2 and OA3 by transferring the patching lead from VS1-S1/I1/SK1 to S2/I1/SK1, and then to S3/I1/SK1, and at the same time reconnecting voltmeters to the appropriate summer and operational amplifier sockets.

### SOFTWARE

Under the heading of "software" comes all the paperwork associated with drawing up a programme for the computer. The time spent on preparing a programme for PEAC can vary from a few minutes to several days, depending on the skill of the programmer and the nature and complexity of the problem.

The intention is to give a few typical programme examples as an introduction to using the computer.



They will consist of a short written *routine*, plus programme layouts. The layouts will be in a duplicated form, of symbolised diagram and patching circuit, so that the reader can compare analogue computer symbols with actual circuits and patching procedures. A newcomer to analogue computers will best learn programming techniques by working with PEAC, and this will also help to increase his knowledge of more advanced mathematics.

### ROLE OF THE OPERATIONAL AMPLIFIER IN EQUATION SOLVING

Now that the time has come to consider UNIT "A" as a computer, instead of as a collection of circuits handling voltages, it is appropriate to adopt a slightly different approach. Voltages will now be replaced by the letters or numbers of an algebraic equation,  $a$ ,  $b$ ,  $c$ ,  $d$ ,  $x$ ,  $y$ ,  $2$ ,  $3$ ,  $4$ ,  $5$ , and so on. Computing resistors lose their individual identity and are considered only as ratios  $\frac{R_f}{R_1}$ ,  $\frac{R_f}{R_2}$ , etc., which are also denoted by equation letters or numbers. The same applies to coefficient potentiometer settings.

**Sign change.** In the circuit of Fig. 4.1a, an input voltage classified as term  $a$ , reappears at the op-amp

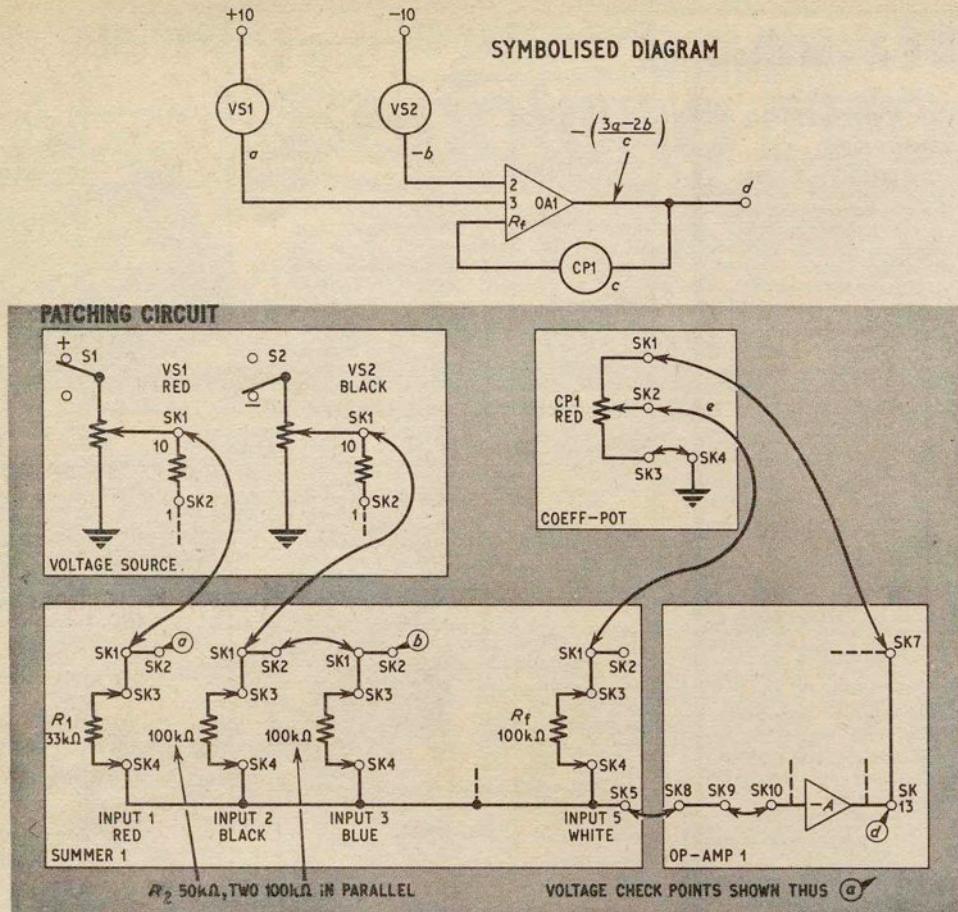


Fig. 4.2 Programme layouts for  $\frac{3a-2b}{c} = d$

output as term  $-a$ , when the  $\frac{R_f}{R_{in}}$  ratio is unity. One way of looking at this operation, which is common to all single operational amplifier configurations, is to assume that  $a$  has been multiplied by  $-1$ , hence  $\frac{R_f}{R_{in}} = -1$ . In effect, to multiply by  $-1$  is to move a mathematical term from one side of its equation to the other, so sign change can be used to transpose.

The operational symbol of Fig. 4.1a avoids the bother of inserting resistors and their values when drawing up a programme layout on paper. The figure inside the triangle—in this case “1”—merely indicates that the computing resistor ratio, or alternatively the operational amplifier gain, is unity.

**Addition.** In Fig. 4.1b, positive terms  $a$  and  $b$  are added to yield an output  $-(a+b)$ , which can also be written  $-a-b$ . If  $-(a+b)$  is applied as an input to a second unity gain operational amplifier, to give two sign changes, it will be converted to  $a+b$ . Note that the figures in the operational symbol triangle show that  $\frac{R_f}{R_1} = 1$ , and  $\frac{R_f}{R_2} = 1$ .

**Subtraction.** The only difference between Fig. 4.2b and Fig. 4.2c is that term  $b$  has been made a negative quantity. The operational amplifier output is therefore  $-(a-b)$  or  $-a+b$ .

**Multiplication.** In Fig. 4.1d,  $R_f$  and  $R_{in}$  are adjusted so that  $\frac{R_f}{R_{in}} = b$ . Hence,  $a$  is multiplied by factor  $b$  to become an output  $-ab$ . The letter inside the operational symbol triangle shows that the  $\frac{R_f}{R_{in}}$  ratio is  $b$ .

Fig. 4.1e gives an alternative method of achieving multiplication. A computing potentiometer is connected to the op-amp input to multiply  $a$  by a factor  $b$ . Therefore, with an input  $ab$ , and  $\frac{R_f}{R_{in}}$  adjusted to equal  $c$ , the result is an output  $-abc$ .

**Division.** When a computing potentiometer is wired as in Fig. 4.1f, with  $R_f$  connected to its slider, term  $a$  will be divided by constant  $b$  when  $R_f = R_{in}$ . Note that  $R_f$  is written inside the symbol triangle to show that  $b$  is a divisor.

It can sometimes happen that a feedback resistor is inadvertently left plugged into an operational amplifier when it is re-programmed for a division operation, and this will result in the circuit of Fig. 4.1g. Instead of an output  $-\frac{a}{b}$  the operational amplifier will yield  $-\left(\frac{a}{b+1}\right)$ .

## COMBINED OPERATIONS

The configurations of Fig. 4.1 have many similarities, which lead naturally to the combination of several operations. In fact, it is possible to perform, say, ten additions or subtractions, three multiplications, and one division operation all at once using a single operational amplifier with several inputs and coefficient potentiometers.

### PROBLEM EXAMPLE 1. SOLVING A SIMPLE EQUATION

UNIT "A" can solve a linear algebraic equation consisting of more than ten unlike terms, but a simple example with only four terms will serve as an adequate practical introduction to programming.

$$\frac{3a - 2b}{c} = d \quad (\text{Eq. 4.1})$$

the letters  $a$ ,  $b$ , and  $c$  are regarded as known quantities, and  $d$  is the unknown, but the equation can be transposed to solve for any unknown.

Eq. 4.1 is implemented on the computer as shown in the Fig. 4.2 patching circuit. Two voltages corresponding to  $a$  and  $-b$  are taken from the voltage source to summer S1, where  $a$  is multiplied by  $\frac{R_t}{R_1} = 3$ , and  $-b$

is multiplied by  $\frac{R_t}{R_2} = 2$ .

The machine equation for the problem is,

$$\frac{R_t a - R_t b}{c} = d \quad (\text{Eq. 4.2})$$

and if  $R_t$  is made 100 kilohm the equation will take the form of

$$\frac{100}{33} a - \frac{100}{50} b = d \quad (\text{Eq. 4.3})$$

Computing resistor values could equally well be  $R_t = 10$  kilohm,  $R_1 = 3.3$  kilohm, and  $R_2 = 5$  kilohm, to yield the same multiplication ratios. Since a 50 kilohm resistor is not included in the short list of Table 4.1, two 100 kilohm resistors are patched together in parallel in the patching circuit Fig. 4.2.

**Routine.** To set up Eq. 4.1 on UNIT "A", first of all ensure that the voltage source switch S6 is off. Insert computing resistors into the positions shown in Fig. 4.2 patching circuit, and connect the computing elements together with patching leads. Set VS1 and VS2 dials to zero, and CP1 to "10", corresponding to a divisor of 1. Wire a voltmeter to OA1/SK13 and zero-set the operational amplifier by means of VR15. Next connect a voltmeter to S1/I1/SK2, and switch on S6. Set VS1 dial for a trial value of  $a = 2V$ . Transfer the voltmeter from S1/I1/SK2 to S1/I3/SK2, and set VS2 dial for a trial value of  $b = -2V$ .

UNIT "A" will now be computing

$$\frac{(3 \times 2) - (2 \times 2)}{1} = 2 \quad (\text{Eq. 4.4})$$

with  $a = 2$ ,  $b = -2$ ,  $c = 1$ , and therefore  $d = 2$ . When a voltmeter is linked to OA1/SK13 it will be discovered that the output voltage  $d$  is actually  $-2V$ , due to the operational amplifier sign change. Remedy by reversing the readout meter leads. If the output voltage is not exactly  $-2V$ , recheck voltages for  $a$  and  $-b$ . To check the exact setting of CP1 dial for any value of  $c$ , temporarily remove the patching lead from CP1/SK1. Patch CP1/SK1 to a precise  $+10V$  from a

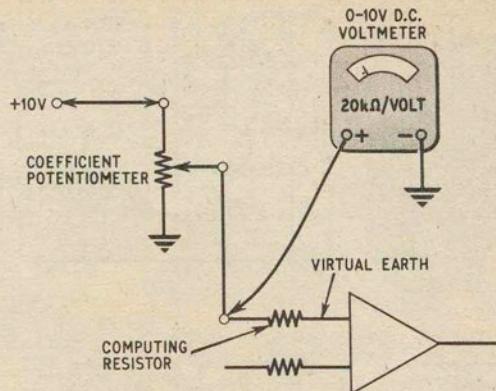


Fig. 4.3. Voltmeter method of determining coefficient potentiometer settings

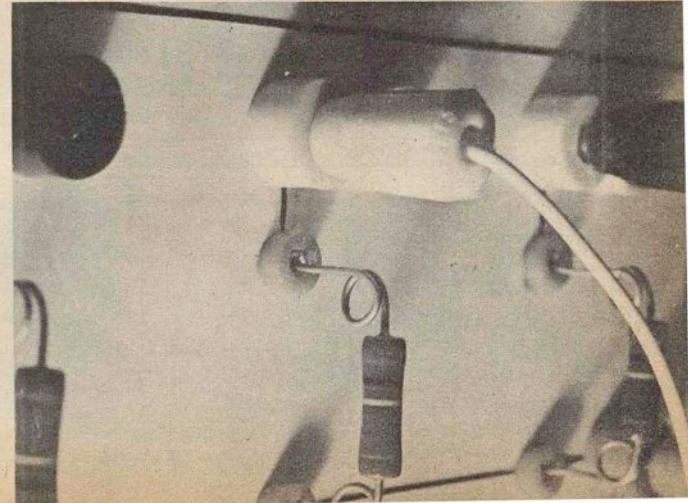
spare voltage source output, and connect a voltmeter to S1/I5/SK2. The voltmeter will then indicate the potentiometer coefficient while taking into account the loading effect of  $R_t$  (see Fig. 4.3). A voltmeter reading of  $4.75V$  is equivalent to a coefficient of  $0.475$ . CP1 can now be patched back into the problem set-up. With a 100 kilohm resistor for  $R_t$ , CP1 will be dividing by numbers equal to or less than unity. If  $R_t$  is changed to 10 kilohm, the range covered by CP1 will become 0-10. Therefore, increasing  $c$  by a factor of 10 can be seen quite clearly to be the same as decreasing computing resistor ratios by a factor of 10.

With UNIT "A" now programmed for Eq. 4.1, it is possible to investigate fully the problem for all reasonable values of  $a$ ,  $b$ ,  $c$ , and  $d$ , and for any unknown without the need for transposing terms or altering the problem set-up. For example, to find  $a$  when  $b$ ,  $c$ , and  $d$  are known, set  $b$  and  $c$  and adjust  $a$  for an operational amplifier output equal to  $d$ . Always monitor an input voltage with a voltmeter when it is being adjusted.

To see how serious computing errors can occur at extreme limits, set VS1 and VS2 so that terms  $3a$  and  $-2b$  are virtually equal, and  $d \approx 0$ . Also, set CP1 to near zero and observe that  $d$  will pass beyond the 10V operational amplifier maximum output swing.

### PROBLEM EXAMPLE 2. ANALYSIS OF VOLTAGE DIVIDER CIRCUIT

The voltage divider of Fig. 4.4a is often encountered in electronic circuits. At first sight, a network consisting of only two resistors might be considered far too simple to merit investigation by means of a computer,



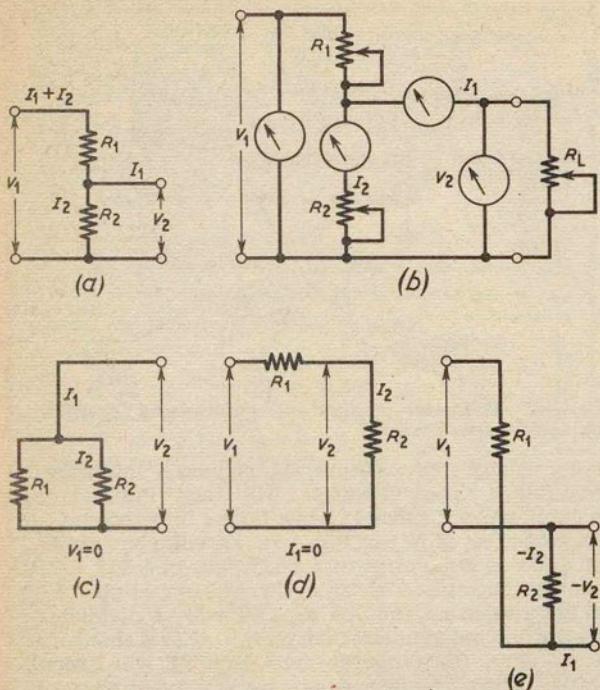


Fig. 4.4. (a) voltage divider circuit; (b) direct simulation of (a); (c), (d) and (e), three variations on (a)

but it does involve at least six variable quantities \$V\_1\$, \$V\_2\$, \$I\_1\$, \$I\_2\$, \$R\_1\$, and \$R\_2\$, and to solve a problem for any unknown, one of six equations would be required, based on

$$R_1 = \frac{V_1 - V_2}{I_1 + I_2} \quad (\text{Eq. 4.5})$$

and

$$R_2 = \frac{V_2}{I_2} \quad (\text{Eq. 4.6})$$

Thus, although it would be ridiculous to use the computer to find one specific answer to one particular voltage divider problem, the paperwork involved in solving six equations for several sets of variables could become surprisingly laborious. What the computer does in fact allow is the solution to literally any voltage divider problem under any conditions, without the need for re-programming.

To solve Eq. 4.5 and Eq. 4.6 simultaneously on UNIT "A", the equations are first transposed for terms \$V\_2\$ and \$I\_2\$, which are common to both.

$$V_2 = V_1 - R_1(I_1 + I_2) \quad (\text{Eq. 4.7})$$

and

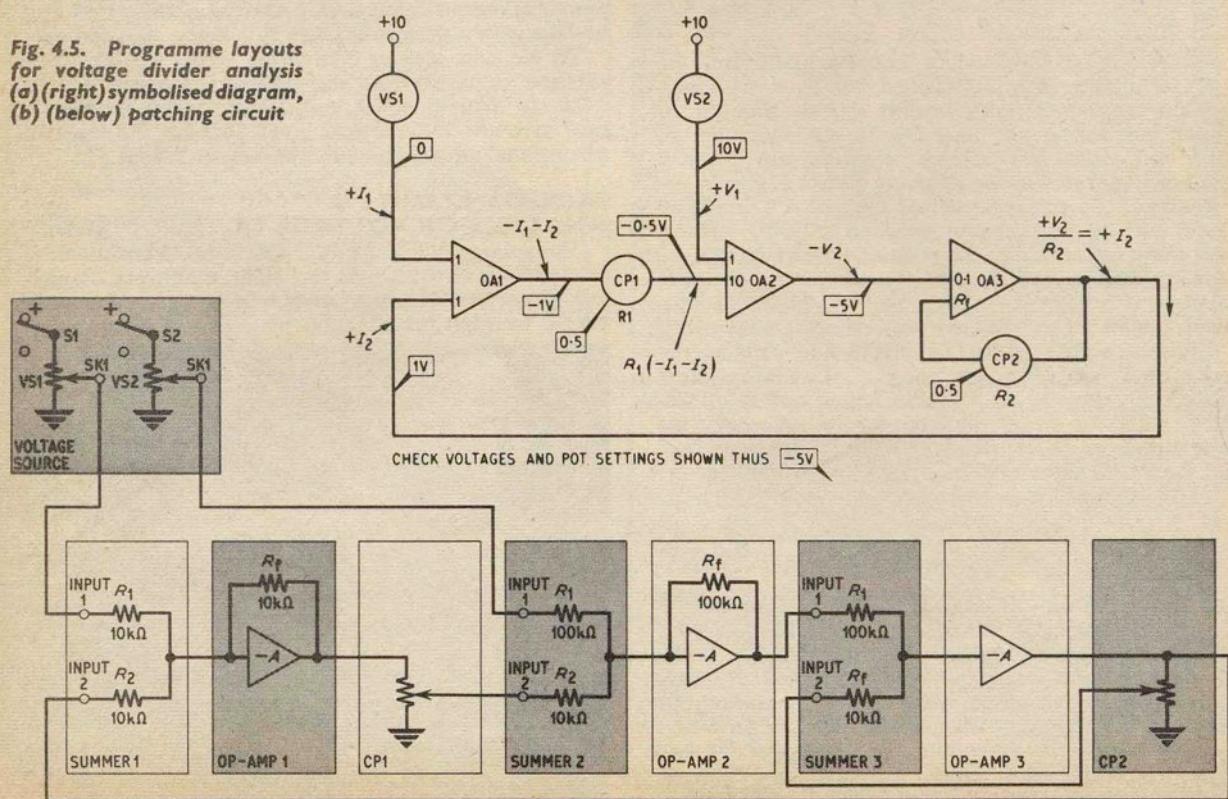
$$I_2 = \frac{V_2}{R_2} \quad (\text{Eq. 4.8})$$

Next, both equations are linked to give a self-enforcing system, shown diagrammatically as,

$$V_1 - R_1(I_1 + I_2) = V_2 \xrightarrow{\uparrow} \frac{V_2}{R_2} = I_2$$

where the answer to Eq. 4.5 is one of the terms of Eq. 4.6 (\$V\_2\$), and the answer to Eq. 4.6 is one of the

Fig. 4.5. Programme layouts for voltage divider analysis  
(a)(right) symbolised diagram,  
(b) (below) patching circuit



terms of Eq. 4.5 ( $I_2$ ). To see how the problem is set-up on the computer, refer to Fig. 4.5, and note the changes of sign involved.

**Routine.** Switch off S6 and insert all computing resistors and patching leads, except the link between OA3 output and OA1 input, which carries the voltage analogue of  $I_2$ . Zero-set OA1, OA2, and OA3 in that order, using a voltmeter applied to each operational amplifier output socket in turn. Now patch the link between OA3 output and OA1 input into circuit. Set VS1 to "0", and VS2 to "+10". The voltmeter method of Fig. 4.3 is employed to set CP1 and CP2 both for a coefficient of 0.5. Temporarily remove the patching leads from CP1/SK1 and CP2/SK1, and connect the "top end" of the potentiometer tracks to a 10V reference voltage. Adjust CP1 and CP2 for outputs of 5V. Exactly the same procedure is adopted when it is necessary to "read off" values for  $R_1$  and  $R_2$ , although approximate readings can be taken from CP1, CP2 dials.

The check voltages in the diagram of Fig. 4.5 correspond to the above voltage source and coefficient potentiometer settings, and provided that there is general agreement with Ohm's law, any desired values can be given to the voltages, currents, and resistances in Fig. 4.4a. The check voltages could apply to actual voltage divider quantities of, say,  $V_1 = 10V$ ,  $V_2 = 5V$ ,  $I_1 = 0mA$ ,  $I_2 = 1mA$  (1 machine volt = 1mA),  $R_1 = 5$  kilohm, and  $R_2 = 5$  kilohm, where VS1 covers the range 0-10mA, VS2 0-10V, CPI 0-10 kilohm, and CP2 0-10 kilohm. Suppose instead that  $V_1$  had been assigned the value of 1,000V, when  $R_1$  and  $R_2$  were both only 5 ohms. One machine volt would now be equivalent to 100A, and  $V_2$  would equal 500V. The ranges covered by computing potentiometers in the latter case would then be VS1 0-100A, VS2 0-1,000V, CPI 0-100, and CP2 0-10 ohms.

Unless informed otherwise, the computer assumes that  $V_1$  is an ideal voltage which originates from a source of infinitely small resistance. Hence, if  $V_1 = 0$ , this corresponds to a short-circuit, and gives the variation of Fig. 4.4c. Alternatively, if  $I_2$  is made equal to nought, the voltage divider circuit is transformed into a load resistor  $R_2$  in series with a source resistor  $R_1$ , given by Fig. 4.4d.

One further variation will serve to show the flexibility of the programme. In Fig. 4.4e the resistance network  $R_1$  and  $R_2$  is made to couple two sources of voltage  $V_1$  and  $-V_2$ , and this occurs when  $I_1$  is made larger than  $I_2 + I_3$ , or in other words, when  $I_2$  swings negative.

The layout of Problem Example 2 is an instance of indirect simulation, where the computer solves equations and imitates the behaviour of the simulated circuit. In this indirect "model" of a voltage divider, relationships between governing equations and actual circuit parameters are made obvious, and the abstractions of mathematics are brought to life as tangible voltmeter and dial readings.

Another way of simulating the Fig. 4.4a circuit is by a direct "model", shown in Fig. 4.4b, which employs coefficient potentiometers for  $R_1$ ,  $R_L$ , and  $R_{L'}$ , voltmeters for  $V_1$  and  $V_2$ , and current meters for  $I_1$  and  $I_2$ . Although feasible, the direct model is less elegant, is not so adaptable to extreme cases, and is subject to errors which do not occur when the voltage divider is simulated indirectly.

**Next month:** Using UNIT "A" to solve a second order differential equation. Indirect simulation of LC circuits, spring pendulums, and servomechanisms by means of integrators.

## REGULATED POWER SUPPLY

continued from page 284

	VOLTS						mA	A
	A	B	C	D	E	F		
No load current	1.0	0.17	14.2	0.68	0.47	2	65	2.7
	2.88	0.145	11.4	0.5	0.38	6	40	2.1
	5.8	0.12	7.0	0.36	0.28	12	18	1.4
1A Load	0.99	0.165	14.1	0.61	0.40	2	36	1.9
	2.86	0.143	11.3	0.41	0.30	6	18	1.3
	5.78	0.119	6.9	0.23	0.17	12	3.5	0.32

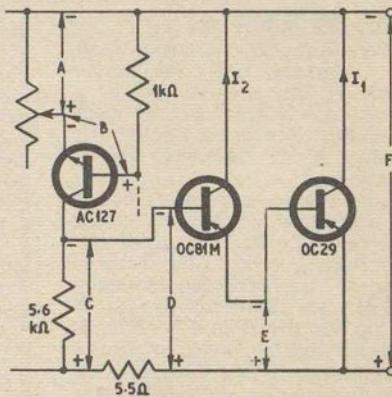


Fig. 10. Test measurements for fault-finding

## CALIBRATION OF OUTPUT VOLTAGE

After checking the voltmeter accuracy against an AVO or similar instrument known to have good accuracy itself, the Regulated Volts dial should be adjusted as follows.

Switch S2 to "Regulated" and S3 to "Volts" and turn VR1 until 1V is obtained at the output (best seen on the AVO). Loosen the knob and rotate to indicate 1V on the calibrated dial. Lock the pointer knob grub screw while indicating the correct 1V. Rotate VR1 until the dial indicates 12V output. Now adjust VR2 until 12V output (measured) is obtained.

## VOLTAGE CHART

Fig. 10 gives typical voltages at six points in the d.c. amplifier circuit for three different output voltages. Reference to these voltages and to the currents of the super-alpha pair TR2, TR3 should assist in any fault-finding.

### INDEX

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**T**HE detailed explanation concerning the operation of UNIT "A" is continued in this month's article, with further practical examples.

We resume by considering the use of the operational amplifier as an integrator.

An operational amplifier will be handling time as well as voltage when acting as an integrator, so some means must be found of inserting intervals of time onto the computer. One method is to employ external oscillators to provide known functions of time in terms of frequency. An input to an integrator might consist of a steady d.c. voltage which is switched on for a time  $t$  (step function or square wave), or alternatively, a sinusoidal voltage of frequency  $f$  and period  $1/f$ .

If a graph is drawn of the resulting integrator output function, and this is the form that answers to problems involving change or motion will usually take, the X axis of the graph will be calibrated in intervals of time, with voltage on the Y axis. It follows that an oscilloscope, which also uses time on the X axis and voltage on the Y axis, can provide a convenient form of output display, especially when an integrator is operating at high speed.

The operational amplifier is converted to an integrator when a capacitor  $C_1$  is inserted, in place of a resistor, in the feedback path; see Fig. 5.1. When an input voltage  $-E_{in}$  is applied to the integrator by means of a simple switch  $S$  for a time  $t$ , the output  $E_o$  will take the form of an increasing ramp voltage proportional to  $t$  with slope

$$-E_{in} \frac{1}{R_{in}C_1}$$

Note that the operational amplifier will continue to invert an input voltage even when used as an integrator.

### THE INTEGRATOR IN EQUATION SOLVING

The electronic analogue computer does provide a powerful technique for obtaining rapid solutions to problems involving calculus, which cannot be equalled either by numerical methods or by a digital computer.

If differentiation and integration are regarded as straightforward mathematical operations, it will be found that the terms of, say, a second order differential equation can be manipulated on the computer in much the same way as the terms of a "steady state" algebraic equation.

For example, when an equation term  $y$  is differentiated against time its derivative  $dy/dt$  is obtained, and a second differentiation yields the second derivative  $d^2y/dt^2$ . The reverse process is where integration of the second derivative  $d^2y/dt^2$  produces the first derivative  $dy/dt$ , and another integration gives  $y$  as the result.

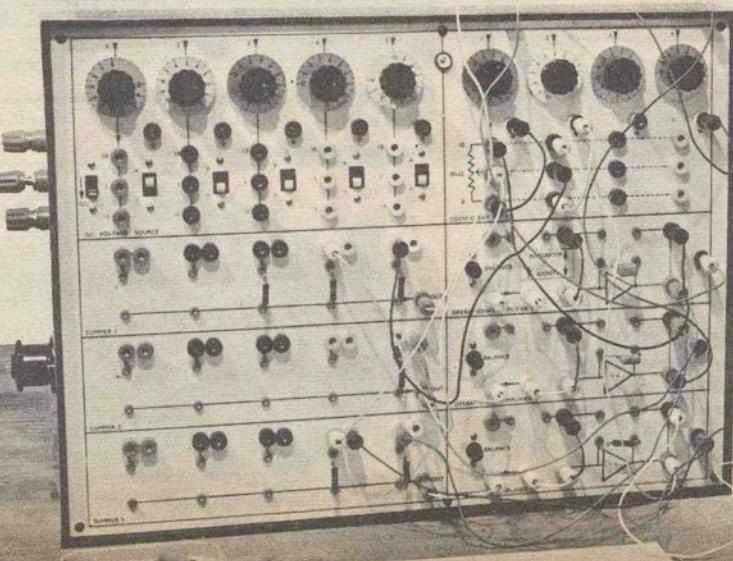
Fig. 5.2 shows how a simple integrator can handle equation terms. Combined operations are made possible by cascading integrators, while using coefficient potentiometers and computing component ratios for summation, multiplication, and division (Fig. 4.1).

The process of differentiation, although feasible if care is taken, is generally avoided on analogue computers because it gives rise to unstable operational amplifier configurations, but this imposes only a slight limitation since integration can be employed—in the majority of cases—in place of differentiation.

### INTEGRATOR ACCURACY

The transfer accuracy of an operational amplifier, when it is used as an integrator, will be theoretically limited by its finite value of open-loop gain. However,

# ANALOGUE COMPUTER



**PEAC**

**By  
D. BOLLEN**

TABLE 5.1

$C_f$	$R_{in}$	$t$
$1\mu F$	$100k\Omega$	$2.8sec$
	$10k\Omega$	$800ms$
$0.1\mu F$	$100k\Omega$	$280ms$
	$10k\Omega$	$80ms$
$0.01\mu F$	$100k\Omega$	$28ms$

Maximum value of  $t$  for an error of 1%

the situation is much more complicated than with, for example, a summing amplifier (Fig. 3.8) since the amplifier error can no longer be defined in terms of the simple relationship between closed-loop and open-loop gains.

As a guiding principle, integrating amplifiers may have very large values of closed-loop gain provided that the time  $t$  of an input function remains small. Closed-loop integrator gains of 1,000 or more are not uncommon in transistor computers, since low voltages and low impedances discourage the use of computing resistors of more than 100 kilohm, and capacitors of more than  $1\mu F$  are too bulky. Table 5.1 is calculated for UNIT "A" amplifiers, and sets out the maximum allowable interval  $t$  for selected values of  $C_f$  and  $R_{in}$ , where the amplifier transfer error must not exceed one per cent.

Errors due to unwanted drift voltages also become significant when  $t$  is long and  $C_f$  is small. The greatest care must be exercised when zero-setting integrators to eliminate offset voltages, for good accuracy at long time intervals. Also, the computer should not be subjected to fluctuations of ambient temperature when computations cover several hours of integrator use.

### COMPUTING CAPACITORS

The computing capacitors used for PEAC will normally lie within the range  $0.01\text{--}1\mu F$ , and the three values most commonly employed are  $0.01\mu F$ ,  $0.1\mu F$ , and  $1\mu F$ . Polystyrene is the preferred capacitor dielectric, for high insulation resistance, but polyester makes an acceptable second best. Mica, paper, and ceramic capacitors should be avoided.

Small value polystyrene capacitors of  $\pm 1$  per cent and  $\pm 2$  per cent tolerance are easily obtained, but  $0.1\mu F$  and  $1\mu F$  precision components are rare and expensive. To get around this difficulty, the bridge circuit of Fig. 5.3 was devised to allow computing capacitors to be made up from specially selected low cost  $\pm 20$  per cent capacitors.

The circuit of Fig. 5.3 can be constructed in breadboard form on Veroboard or s.r.b.p., with miniature sockets to take  $C_x$  and  $R_1$ . If an audio signal generator is not available to supply the bridge with about 10V r.m.s. at 1kHz, a signal could be obtained from a transistor multivibrator powered by the 25V computer power supply. Headphones serve to detect the null point when the bridge is in balance, and should have an impedance of about 2 kilohms.

The method of making up a computing capacitor of, say,  $1\mu F$  is as follows. A capacitor panel of plain or perforated s.r.b.p. is fitted with small turret tags as in Fig. 5.4. A  $\pm 20$  per cent capacitor of about  $0.68\mu F$  is wired into position on the capacitor panel before it is plugged into the bridge  $C_x$  sockets, and a 1 kilohm

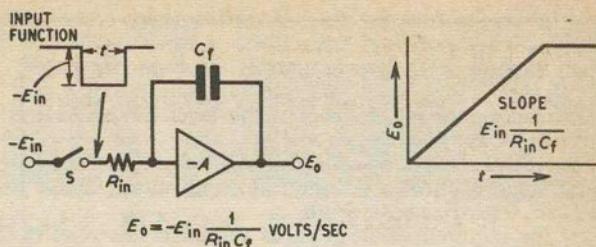


Fig. 5.1. The operational amplifier as an integrator

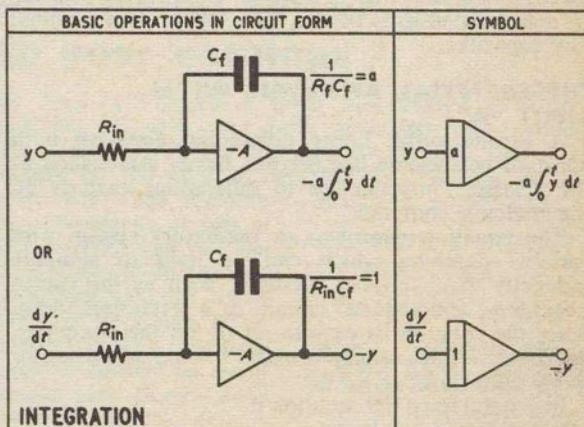


Fig. 5.2. The handling of equation terms by a simple integrator

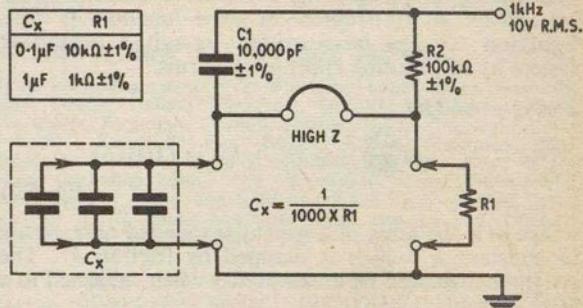


Fig. 5.3. Bridge circuit used for making up computing capacitors

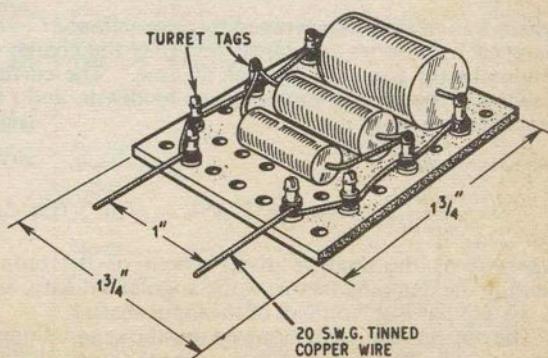


Fig. 5.4. Computing capacitor plug-in panel

resistor is inserted for R1. Assorted polystyrene or good quality polyester capacitors of lower value are then temporarily connected across the capacitor panel to increase  $C_x$  by small increments, while listening on the headphones for a drop in the level of the 1kHz tone as  $C_x$  approaches  $1\mu F$ .

A typical computing capacitor might finally consist of a parallel combination of the following values,  $0.68\mu F$ ,  $0.22\mu F$ ,  $0.02\mu F$ , and  $0.005\mu F$ .

If the required value of  $C_x$  is exceeded, the note in the headphones will increase in volume when the null point is passed. Allow capacitors to cool off after soldering, and before making a measurement, as heat can cause a temporary or permanent change in capacitance. With the Fig. 5.3 bridge circuit it is possible to detect increments of less than  $0.01\mu F$  in a nominal  $1\mu F$  capacitor.

### DIFFERENTIAL ANALYSIS WITH UNIT "A"

A second order linear differential equation with constant coefficients has become firmly established as the "classic" introduction to differential analysis on the analogue computer.

The equation describes an oscillatory system with variable damping which can be used to simulate indirectly many physical systems, such as the spring pendulum, a tuned LC circuit, or a servomechanism. Also, the equation is easy to set up on the computer, and does not necessarily demand the use of integrator mode switching.

In general form the equation is,

$$a \frac{d^2y}{dt^2} + b \frac{dy}{dt} + cy = f(t) \quad (\text{Eq. 5.1})$$

where  $a$ ,  $b$ , and  $c$  are the constant coefficients,  $y$  is unknown, and  $f(t)$  represents some function of time. Equation 5.1 can be rewritten to suit a particular system by substituting appropriate terms.

#### Spring pendulum

$$m \frac{d^2y}{dt^2} + \mu \frac{dy}{dt} + ky = f(t) \quad (\text{Eq. 5.2})$$

where  $m$  is the mass of a weight suspended on a spring of constant  $k$ , which is damped by friction  $\mu$ . The weight is displaced by an amount  $y$  when subjected to a force dependent on  $f(t)$ .

#### Tuned LC circuit

$$L \frac{d^2Q}{dt^2} + R \frac{dQ}{dt} + \frac{1}{C} Q = f(t) \quad (\text{Eq. 5.3})$$

where  $L$  is an inductance tuned by a capacitance  $C$ , and damped by a series resistance  $R$ .  $Q$  is the charge in coulombs on  $C$  at any instant of time. The current flowing in the tuned circuit is given by  $dQ/dt$ , and  $f(t)$  represents an input function.

#### Servomechanism

$$\frac{d^2\theta_o}{dt^2} + 2\zeta\omega \frac{d\theta_o}{dt} + \omega^2\theta_o = \omega^2\theta_i \quad (\text{Eq. 5.4})$$

where  $\theta_o$  is the angular displacement of the output shaft,  $\zeta$  the damping factor,  $\omega$  the angular velocity, and  $\theta_i$  the angular displacement of the input shaft.

The obvious similarity between the above equations is emphasised when, in Fig. 5.5, it is seen that they all have virtually the same problem layout on the computer.

Furthermore, as the computer will allow operation at almost any fraction or multiple of real time, a spring pendulum and a tuned LC circuit can be simulated simultaneously, and interesting electro-mechanical parallels can be seen to exist between the properties of inductance and mass, resistance and friction, and capacitance and elasticity.

The only real difference between the analogous behaviour of a weight on a spring, a servo shaft, and a tuned LC circuit is that the LC combination will normally resonate at a much higher frequency.

### PROBLEM EXAMPLE 3. TUNED CIRCUIT ANALYSIS

UNIT "A" will simulate any series tuned circuit by solving Equation 5.2, and will give answers in the form of a.c. meter readings or oscilloscopes. Tuned circuits resonating in the MHz region are catered for by slowing down the problem to some convenient decadal fraction of real time, so that a simulated circuit on the computer which is, for example, resonating at 300Hz, will serve as a model for a real circuit resonating at 30MHz, with suitable rescaling of  $L$ ,  $C$ , and  $t$ .

To initially determine the relative values of  $L$ ,  $C$ ,  $R$ , voltage  $V$ , and current  $I$ , without too much paperwork, it is helpful to start with a representative tuned circuit which allows computer operation in real time, at frequencies convenient for display by an a.c. voltmeter or an oscilloscope. 50Hz is a good frequency to employ as a datum because it can be readily obtained from the mains supply, and rounded values of  $L = 1H$  and  $C = 10\mu F$  will also offer resonance at 50Hz.

Taking the circuit of Fig. 5.6a as a starting point, from the knowledge that a series tuned circuit will exhibit an impedance equal to  $R$  at resonance, the r.m.s. current flow at 50Hz will be  $E_1/R$ , or 20mA when  $E_1 = 2V$  r.m.s. and  $R = 100$  ohms.

It is necessary to rearrange the basic equation, Equation 5.2, for the computer by dividing through by  $L$ , and solving for the second derivative.

$$\frac{d^2Q}{dt^2} = -\frac{R}{L} \frac{dQ}{dt} - \frac{1}{LC} + \frac{f(t)}{L} \quad (\text{Eq. 5.5})$$

Substituting known values from Fig. 5.6a,

$$\frac{d^2Q}{dt^2} = -\frac{100R}{1H} \frac{dQ}{dt} - \frac{1}{1H \times 10^{-5}C} Q + \frac{f(t)}{1H} \quad (\text{Eq. 5.6})$$

$f(t)$  in the present case represents a sine wave input of 2V r.m.s. In other circumstances the input function could be a square wave of amplitude  $E_{in}$  and period  $2t$ .

Equation 5.6 is solved on the computer by successive integration. Looking at the symbolised diagram of Fig. 5.6b, it can be seen that there are two closed-loops, one linking the output of OA1 via CP1 to OA1/Input 1, and the other passing through OA1, OA2, and OA3, via CP2, and thence back to OA1/Input 3. The coefficient of CP1 will be multiplied by the gain factor associated with OA1/Input 1. CP2 coefficient is multiplied by the product of gains OA1/Input 3, OA2, and OA3, i.e.  $1,000 \times 100 \times 1 = 100,000$ .

$d^2Q/dt^2$ , obtained from the sum of the voltages present at the inputs of OA1, is initially assumed to be present. After one integration OA1 provides an output  $dQ/dt$ , and from this all the terms on the right hand side of Equation 5.6 are assembled. So,  $dQ/dt$  is multiplied by  $R/L = 100$ , using CP1 set for a coefficient of 0.1, and is taken back to OA1/Input 1 where it is then added to  $f(t)/L = 2V$  r.m.s.

Moving in the other direction on the symbolised diagram of Fig. 5.6b,  $dQ/dt$  is integrated by OA2 to obtain  $+Q$ . Inverting amplifier OA3 changes the sign of  $Q$  before passing it on for multiplication by  $1/LC = 100,000$  (CP2 coefficient of 1).  $-(1/LC)Q$  is then added, at OA1/Input 3, to

$$-\frac{R}{L} \frac{dQ}{dt} + \frac{f(t)}{L}$$

and the sum of all OA1 input voltages yields the required  $d^2Q/dt^2$ . Because there are two closed-loops in the computer set-up the equation will be self-enforcing.

**Routine.** Switch on UNIT "A" power supply and allow a warm-up time of at least 15 minutes. Ensure that the three operational amplifiers are disconnected from their summer networks, and have no feedback components. Apply 10V d.c. voltmeter leads to OA1/SK13 and an earth socket, and zero-set OA1 for

an output voltage of less than  $\pm 1V$  from the back of the UNIT "A" box, by means of VR1 (Fig. 3.7). Repeat for OA2 and OA3.

Set up the problem according to the patching circuit of Fig. 5.6b, but omit the feedback capacitors and the patching link between OA3/SK13 and CP2/SK1. Set CPI dial to approximately "1". Connect the voltmeter to miniature socket OA1/SK6 (Fig. 2.9) and zero-set OA1 again, but this time using the front panel control VR15.

Next, zero-set OA2 using VR16, and OA3 using VR17. Insert  $0.1\mu F$  computing capacitors into OA1/SK11 and SK12, and OA2/SK11 and SK12, and make good the link between OA3 output and CP2. Set CP2 for a dial reading of "10". Apply the voltmeter to OA2/SK7 and zero-set the complete assembly of amplifiers by adjustment of VR15(OA1) only.

The problem layout will now be ready for dynamic checks and should not need to be re-zeroed for several hours if UNIT "A" is being operated in stable ambient temperature conditions.

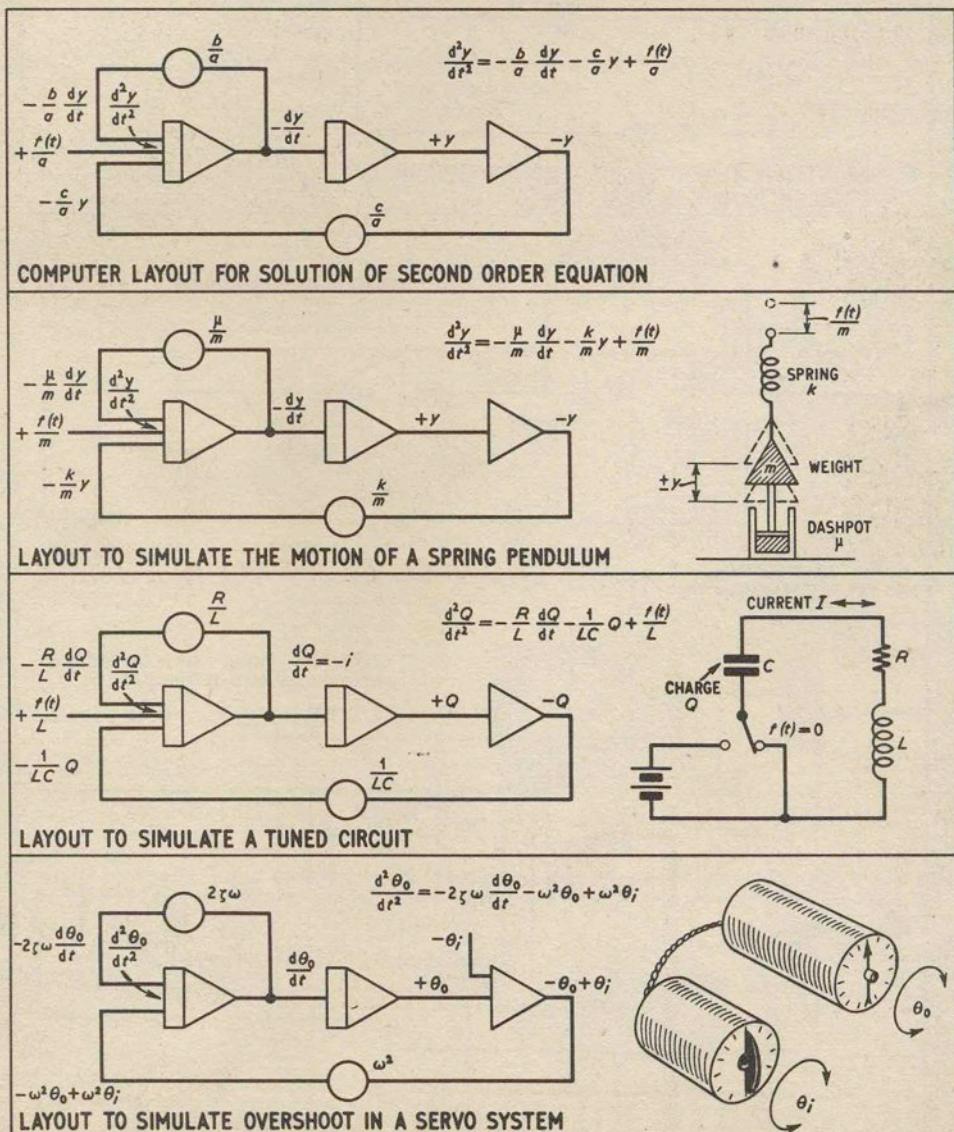


Fig. 5.5. A second order differential equation applied to physical systems

TABLE 5.2  
SHOWING HOW COMPUTER OPERATING FREQUENCIES ARE RELATED TO CP2 SETTING AND AMPLIFIER CLOSED-LOOP GAINS

Resonant Frequency $f$	Typical Values	CP2 Coefficient	$\frac{1}{LC}$	Amplifier Gains
	L      C	Input 3	OA1    OA2    OA3	
0.05Hz to 0.5Hz	1,000H $10,000\mu F$	0.1	0.1	10    10    0.1
5Hz to 50Hz	10H $100\mu F$	1.0	10	10    10    0.1
10Hz to 100Hz	1H $10\mu F$	0.01	$10^3$	1,000    100    1.0
500Hz	100mH $1\mu F$	1.0	$10^5$	1,000    100    1.0
1kHz	100mH $0.2\mu F$	1.0	$5 \times 10^7$	1,000    1,000    50

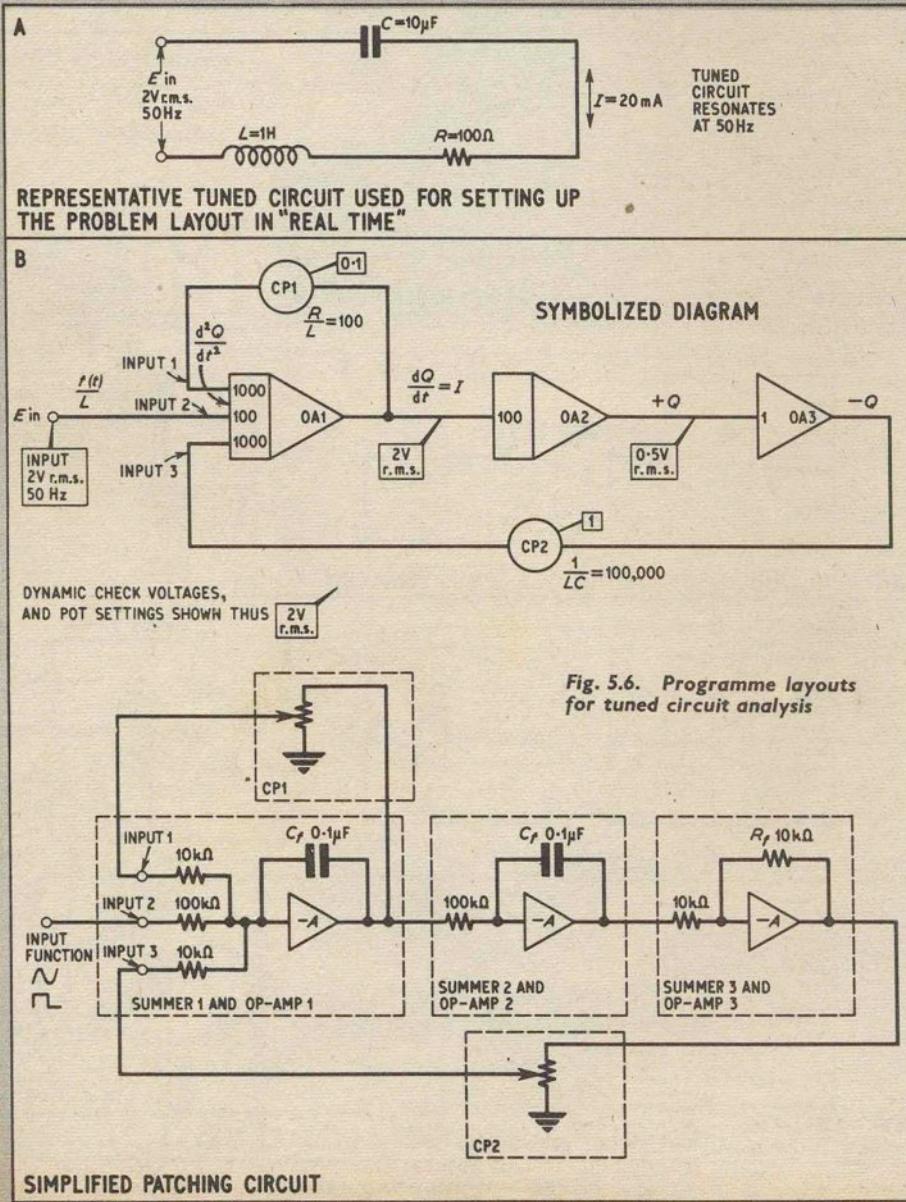


Fig. 5.6. Programme layouts for tuned circuit analysis