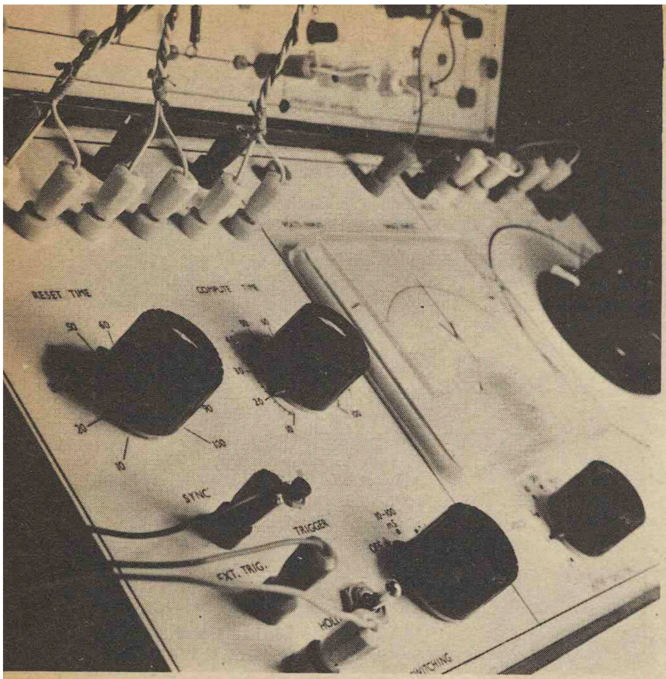


on its blocks, and, following Fig. 6.10 and Fig. 7.3, wire all controls and sockets to the turret tags on the two sub-assembly panels, again with p.v.c. covered flexible wire, long enough to allow the switching circuit panel to be turned over for underside inspection. Run red and blue wires from S9, and a green wire from IS/SK12, to the power pack output solder tags, and fit knobs to S9, VR18, and VR19.

SETTING UP THE INTEGRATOR SWITCH

Time intervals can be measured with fair accuracy when an operational amplifier is employed to integrate known voltages, and this method is useful for setting up the integrator switch.

Begin by temporarily soldering 8μF electrolytic capacitors in the C4 and C8 positions, with 1μF polyester capacitors for C3 and C7 (circuit Fig. 6.10).

Set VR1 and VR2 with sliders at mid-track, on the integrator switch panel.

Connect integrating switch to the operational amplifier by linking IS/SK7 to OA3/SK9, IS/SK8 to OA3/SK10, and IS/SK9 to OA3/SK4. Fit 100 kilohm computing resistor in S3/I1/SK3 and SK4. Join S3/I1/SK1 to VS1/SK2 and switch off S6. Insert a 2 kilohm reset resistor in OA3/SK5 and SK6, and join S3/SK5 to OA3/SK13.

ANALOGUE COMPUTER

PE AC

By D. BOLLEN

To complete the construction of UNIT "B", we have now to deal with the integrator switching section, the circuit diagram for which has already been given, see Fig. 6.10.

INTEGRATOR MODE SWITCH ASSEMBLY

Cut and drill the 6¼in × 2½in s.r.b.p. panel shown in Fig 7.1, and rivet turret tags in the positions shown. From six transistors select two with the highest current gain for TR2 and TR5. Mount all components, except range capacitors C3, C4, C7, and C8, on the s.r.b.p. panel and wire up.

Prepare the 3in × 2in relay panel, from Fig. 7.2. Fix turret tags and mount RLA and RLB reed coils. Next, insert miniature diodes D3–D14, with alternating polarities along the row of diodes, and complete underside wiring. To finish off the relay panel, place three reed switches in each coil and secure by soldering the lead out wires to appropriate turret tags.

Wooden blocks are glued to the rear of the UNIT "B" front panel to serve as mounts for switching circuit panel and relay panel (see Fig. 7.3). Note that the relay panel is fitted end-on into slots cut in its mounting blocks, and the switching circuit panel is secured by two woodscrews.

After first attaching lengths of black and white p.v.c. covered multi-strand wire to the terminals of VR18 and VR19, screw the switching circuit panel in position

Switch on the computer and allow a warm up period before zero setting OA3 from the back of the UNIT "A" box, by means of VR1 on the OA3 amplifier panel. Insert a 1μF computing capacitor into OA3/SK11 and SK12.

With S8 switched to "hold", S9 on the 0·1–1s range, and VR18 and VR19 rotated fully clockwise, press S7 to run the integrating amplifier through reset, compute, and hold sequence.

Listen for two clicks from the reed relays, and observe that the readout meter pointer will move close to zero. If the relays click more than twice, or not at all, adjust VR1 on the integrator switch panel.

To obtain a true zero output from the amplifier, when integrating a zero input voltage, adjust VR17 (OA3 balance control) while repeatedly pressing S7. If there is a slow drift away from zero output several seconds after S7 was last pressed, retrim VR1 on the OA3 amplifier panel.

As the gain of OA3 is set at 10 (1μF for C_f and 100 kilohm for R_{in}), an input of −0·9V "gated" by the integrator switch for an interval of 1s should give rise to an amplifier output of exactly +9V. Switch on S6 and adjust VS1 for −0·9V, monitored at S3/I1/SK2 by a voltmeter.

Now when S7 is pressed, and with VR19 still rotated fully clockwise, the readout meter reading should rise to somewhere below +9V and stay there.

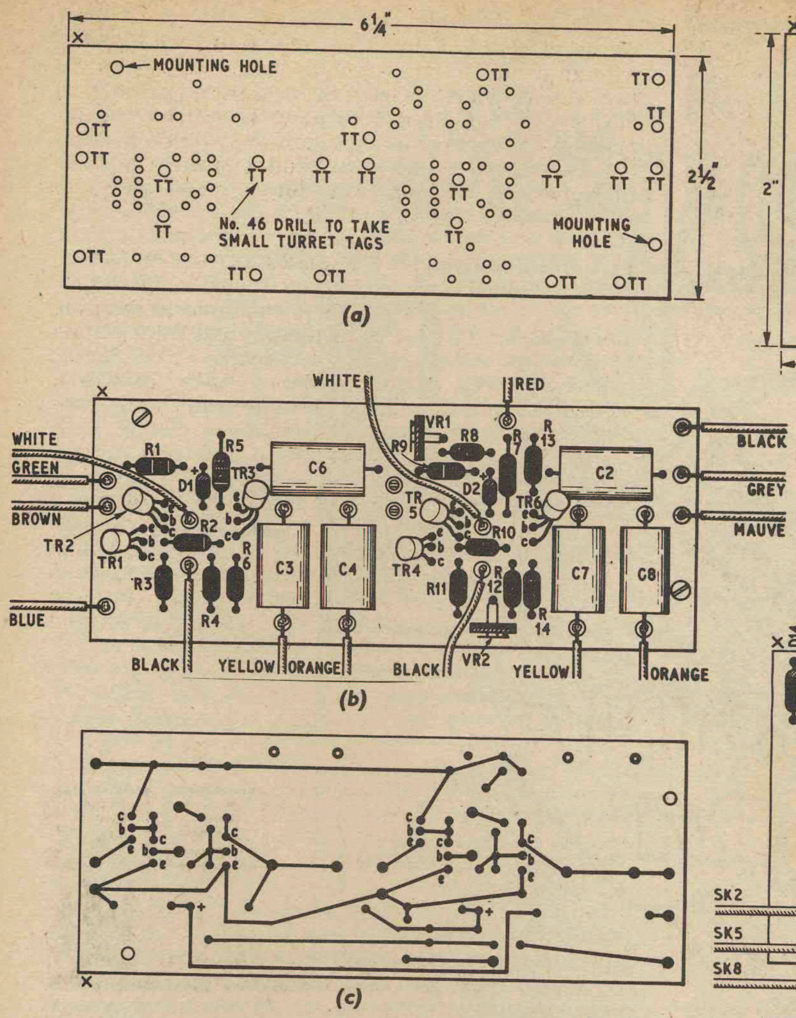


Fig. 7.1. UNIT "B" integrator switch circuit panel, (a) drilling template; (b) component arrangement; (c) underside wiring

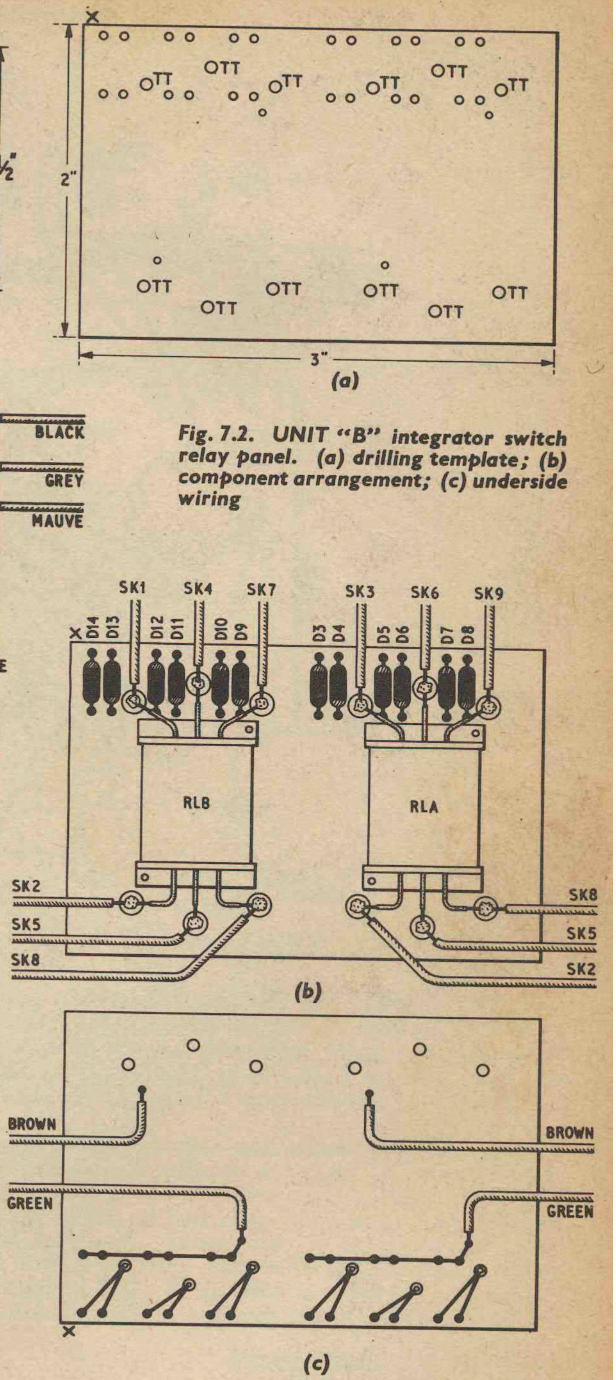
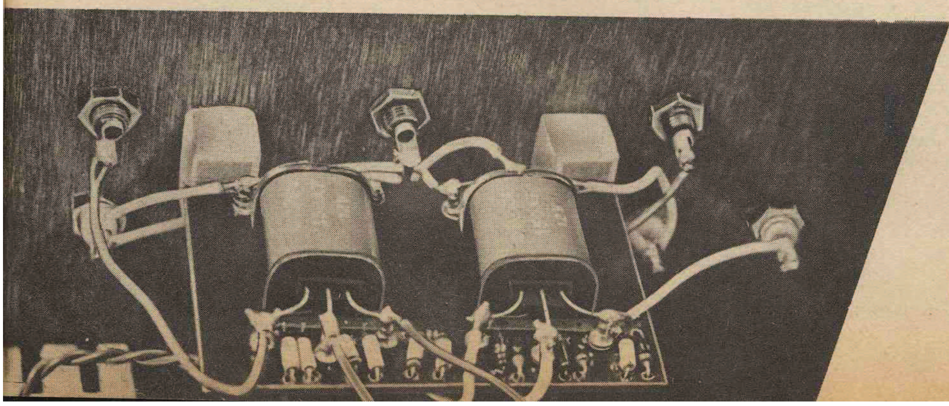


Fig. 7.2. UNIT "B" integrator switch relay panel. (a) drilling template; (b) component arrangement; (c) underside wiring

Build up the value of C8 timing capacitor by adding more capacitors in parallel, until the +9V output is obtained when S7 is pressed.

To check the "fast" end of VR19 scale, set VS1 for −9V and rotate VR19 fully anti-clockwise. Adjust VR2 on the integrator switch panel to obtain the desired amplifier output of +9V for a compute interval of 0·1s.



(c)

Section of UNIT "B" panel (viewed from rear) showing integrator switch relay assembly

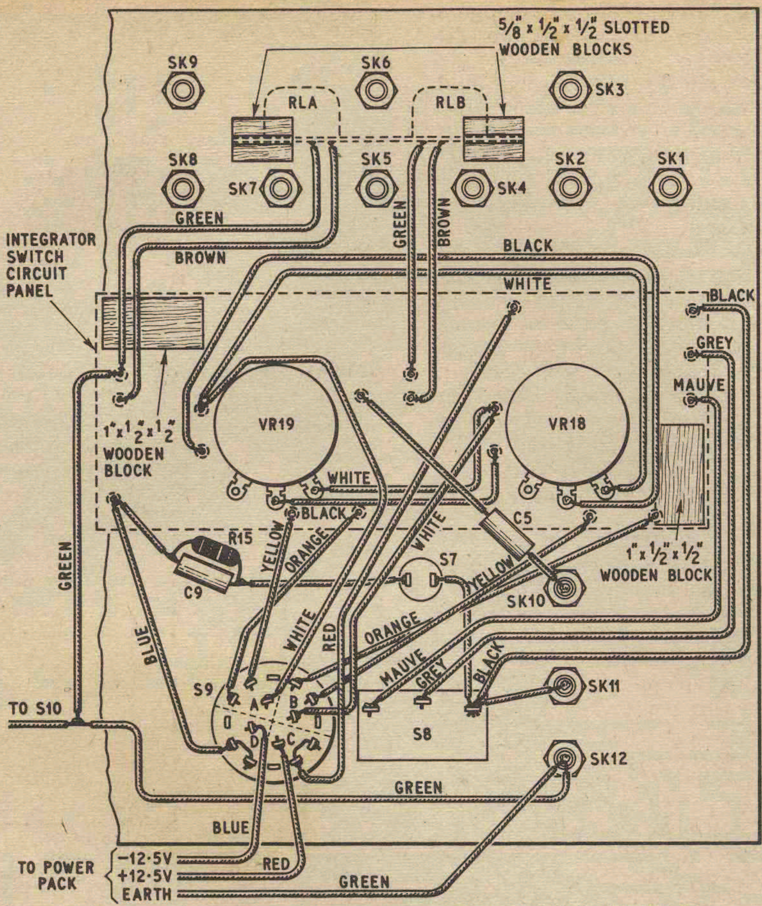


Fig. 7.3. Rear view of UNIT "B" front panel showing integrator switch wiring

CALIBRATING THE SECOND RANGE

To calibrate the 10–100ms S9 range, repeat the above procedures in just the same way, but this time use a 0·1μF capacitor for C_t in sockets OA3/SK11 and SK12, and adjust the value of timing capacitor C7 for correct compute intervals.

1st monostable timing capacitors C3 and C4 need not be precise, as VR18 has no effect on the accuracy of computations, and is mainly used to control the switch cycle frequency when integrator output waveforms are displayed by oscilloscope. Therefore, and merely for the sake of conformity, build up C3 and C4 capacitor values until the coverage of VR18 is approximately as indicated by the reset interval dial calibration.

CIRCUIT ADJUSTMENTS

The Fig 6.10 circuit should operate reliably at all switch and dial settings, with no noticeable relay bounce or overlap between the closure of reset and compute switches. However, it may be found that the integrator switch will stop running during repetitive operation, when reset and compute intervals approach 10ms, despite the fact that VR1 has already been trimmed for optimum performance. If so, try reducing the value of R8.

At the opposite extreme, if the integrator switch suddenly goes into repetitive operation when S8 is at "Hold", and VR18 and VR19 settings are near 1s, increase R8, and also try the effect of doubling the value of C1 to improve decoupling.

PROBLEM EXAMPLE 4

STRAIGHT PATH MOTION OF AN OBJECT

Problem Example 4 is primarily intended as a comprehensive introduction to the use of integrator mode switching, but the programme is sufficiently flexible to allow many experiments in dynamics to be performed.

Several factors can combine to influence the overall motion of an object, and some are shown in the ball problem of Fig. 7.4. A ball thrown vertically into the air will be subject to an initial upward velocity *iv*, retardation or negative acceleration due to gravity $-a$, and air resistance. The situation is further complicated if the ball is projected upwards from an initial height *is*, and is arrested at some height other than zero.

Ignoring for the moment air resistance, the equations which govern the motion of the ball are,

$$v = \int_0^t a\,dt + iv \qquad \text{(Eq. 7.1)}$$

and

$$s = \int_0^t v\,dt + is \qquad \text{(Eq. 7.2)}$$

Clearly, integration of a yields v, and a further integration of v will give s.

The formulae used to calculate velocity or distance when acceleration is constant are,

$$v = iv + at \qquad \text{(Eq. 7.3)}$$

and

$$s = ivt + \tfrac{1}{2}at^2 + is \qquad \text{(Eq. 7.4)}$$

Eq. 7.3 and 7.4 will not apply if, for example, acceleration is proportional to time. A discussion of the implications of variable acceleration lies outside the scope of this series, but time varying voltage analogues of acceleration are fairly easy to generate on the computer.

The drag on a body moving through air or a fluid conforms to an exponential law, and is proportional to velocity when there is little or no turbulence. Viscous friction should not be confused with the friction resulting from solid surfaces in contact, as the latter is independent of velocity except at very low speeds. A general solution to an equation which describes the motion of an object through a viscous medium—where composite velocities are involved—is often unwieldy and can demand extensive calculations.

However, an exponential decay can be set-up on the computer to simulate true viscous friction, in terms of a coefficient value μ which remains constant for all velocities. Nevertheless, as μ will be dependent on such factors as the surface area, shape, and relative smoothness of an object, it can only be determined by practical experiment, or by comparison between the computer solution and the timed motion of an actual object.

Looking at the symbolised diagram of Fig 7.5, OA1 is employed to integrate a known voltage against time, so that t can be conveniently and accurately displayed as a meter reading. OA2 integrates a to give an output v, and at the same time handles the initial velocity iv. The exponential decay $e^{-(\mu/m)t}$ is introduced by CP1. Resulting velocity v is then integrated by OA3 and initial distance is is included to give distance or height s at any time t.

Routine. Set-up the problem according to the simplified patching circuit of Fig. 7.5 but omit for the time being all C_f capacitors. The integrator switch is linked to the three operational amplifiers by connecting IS/SK1 to OA1/SK9, IS/SK2 to OA1/SK10, IS/SK3 to OA1/SK4, IS/SK4 to OA2/SK9, IS/SK5 to OA2/SK10, IS/SK6 to OA2/SK4, IS/SK7 to OA3/SK9, IS/SK8 to OA3/SK10, and IS/SK9 to OA3/SK4.

Allow the computer to warm up before zero-setting the amplifiers, also make sure that S6 is off. Using the readout meter on its 10V range, zero-set amplifier outputs (OA1/SK13, S3/I5/SK2, and OA3/SK13) by means of VR1 on each amplifier panel, from the back of the UNIT "A" box.

Next insert the C_f computing capacitors into amplifier feedback loop sockets (SK11 and SK12) and set the integrator switching controls to give reset and compute times of approximately 0·1 second. Put S8 in the "hold" position. With the readout meter on its 1V range, applied to the output of OA1, press S7 and adjust VR15 for a zero voltage reading. Repeat for OA2 output and VR16, and OA3 output and VR17, in that order. The amplifiers should now be balanced for near zero input offset voltage.

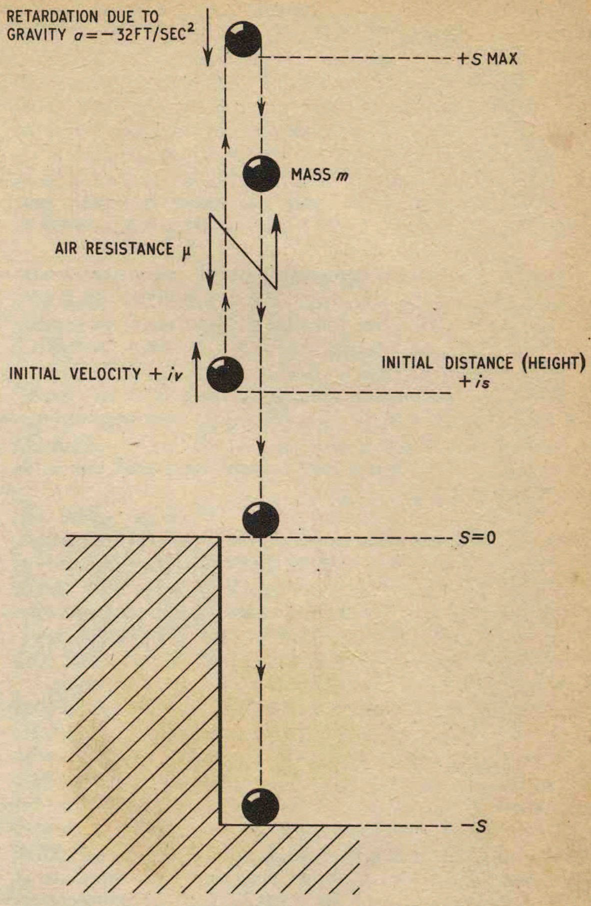
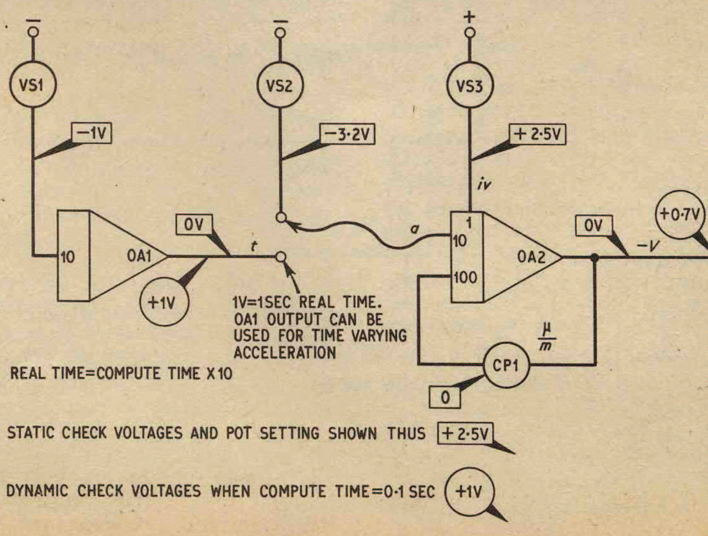


Fig. 7.4. An experiment in dynamics with a ball



	TYPICAL UNITS
a ACCELERATION	FT/SEC^2
V VELOCITY	FT/SEC
S DISTANCE	FT
t TIME	SEC
m MASS	LB
μ VISCOUS FRICTION COEFF.	

Fig. 7.5. Symbolised diagram of the ball problem illustrated in Fig. 7.4.

To enable static and dynamic checks to be made, trial values are given to the ball problem of Fig. 7.4, as follows: $t_{real} = 1$ sec, $a = -32$ft/sec², $iv = 25$ft/sec, $is = 10$ft, $v = -7$ft/sec, $s = 19$ft, and $\mu/m = 0$. The problem scaling is such that 1 computer volt = 10 units in all cases. For example, 1V = 1 sec for t at the output of OA1 (10 × compute time), and 1·9V = 19ft for s at OA3 output. Calculation from the formula Eq. 7.4 shows that the ball will have travelled just beyond s_{max} after a time of 1 sec, when air resistance is zero.

The next stage is to establish all computer static voltages shown in the Fig. 7.5 symbolised diagram, starting with VS1. Set the dial of the master potentiometer to "10" and patch MP/SK1 to SK4, MP/SK2 to SK3, and MP/SK5 to SK8. Connect RM/SK2 to S1/11/SK2. Switch on S6, set switch S10 to "null" and adjust VS1 dial for a null meter reading, corresponding to a voltage source output of − 1V. Remove the null input patching lead completely, and use it to link RM/SK1 to OA1/SK13.

With the readout meter on its 1V range, press S7, and trim compute time control VR19 for an integrator output of 1V; this will ensure that the compute interval is exactly 0·1 sec. Set up VS2, VS3, and VS4 check voltages, preferably by nulling with the master potentiometer to avoid loading, and rotate CP1 fully anti-clockwise. Switch off S6 and press S7 to reset the amplifiers. Check that amplifier outputs are zero.

To obtain dynamic check voltages, switch on S6 and press S7, while applying the readout meter to the outputs of OA1, OA2, and OA3 in turn. For greater convenience, three separate voltmeters can be left connected as shown in the patching circuit of Fig. 7.5 to give simultaneous readouts of t, v, and s. Before altering other problem variables, introduce air resistance by means of CP1 and arrest the travel of the ball at selected positions along its path by adjusting the compute time. It is instructive to compare the velocity and distance of the ball when $a = -32$ft/sec² and friction is present, with a ball projected upwards under moon gravity conditions (approximately $a = -5{\cdot}3$ft/sec²) in a vacuum.

The existing scaling of layout Fig. 7.5 will provide the following coverage: VR2 0–±100ft/sec², VR3 0–±100ft/sec, VR4 0–±100ft, with amplifier outputs of OA1 0·1–10sec, OA2 0–±100ft/sec, and OA3 0–±100ft. The coefficient of CP1 covers the range 0–10 for μ/m.

If at any instant during a computer run velocity exceeds 100ft/sec, or distance is greater than 100ft, this will result in amplifier overloading, and a false problem solution. Spot checks of velocity or distance voltage trends can be made at selected compute times, using the single shot facility, and s_{max} will correspond with $v = 0$ at a particular time t. Alternatively, during repetitive integrator switching, an oscilloscope will serve to show amplifier overloads as a flattening or clipping of an output waveform, but this should not be confused with the short "hold" interval which separates the opening and closing of reset and compute switches.

RESCALING PROBLEM EXAMPLE 4

The programme of Problem Example 4 need not be confined to the vertical motion of an object in air, but could equally well apply to movement up and down an inclined plane in water, or else the horizontal progress of a fast wheeled vehicle being decelerated by braking forces, for example.

There are several ways of rescaling Problem Example 4, the most obvious being the adoption of other unit systems, such as miles/hour, centimetres/sec, or even inches/year. Providing that compatible units are employed, and computer voltages are correctly interpreted, there are no serious barriers to unit system rescaling. Probably the most straightforward way of verifying a new problem scaling is to set up a simple check problem, where known values of t, a, v, and s are computed for an object in a vacuum, to establish the relationships between static and dynamic voltages.

Where it is desired to extend the range of an existing unit system, increasing the value of computing capacitors by a factor of ten will reduce real time by ten. Similarly, a tenfold increase in real time is achieved when C_f values are divided by ten.

When employing large computing capacitors at short compute times, always ensure that the reset resistor R_r is small enough to completely discharge C_f during the reset interval. It is also possible to alter the computer voltage scaling so that, for example, 1 computer volt will equal 100 units instead of 10 units, but care should be taken to make sure that *all* voltages and potentiometer settings conform to the new scaling.

Finally, a word or two about variable acceleration. If the input to OA2 is transferred from the VS2 source to the output of OA1, acceleration will then be zero

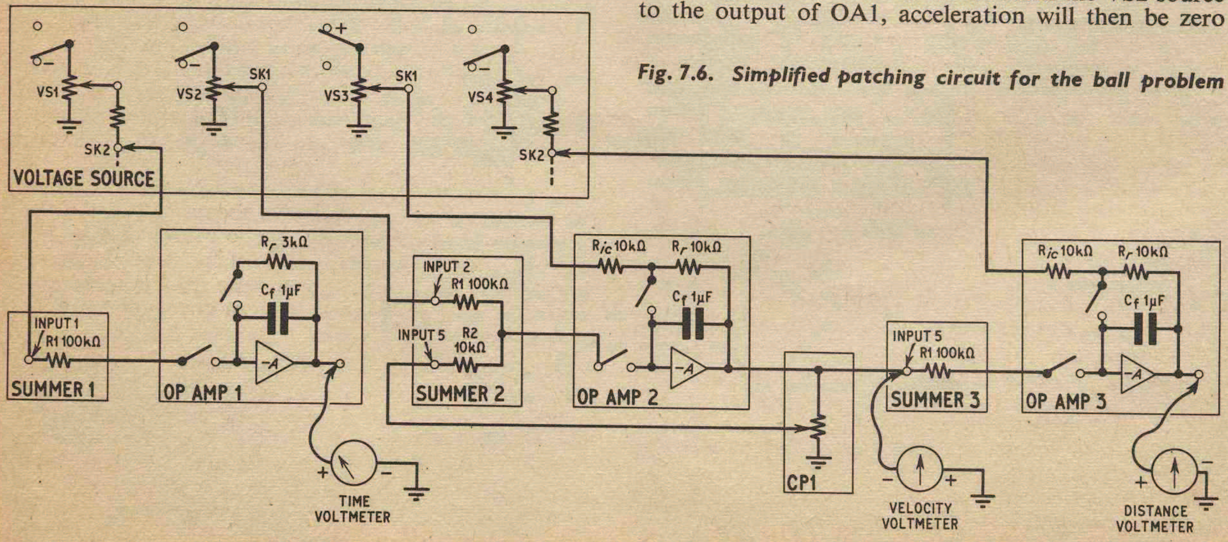


Fig. 7.6. Simplified patching circuit for the ball problem

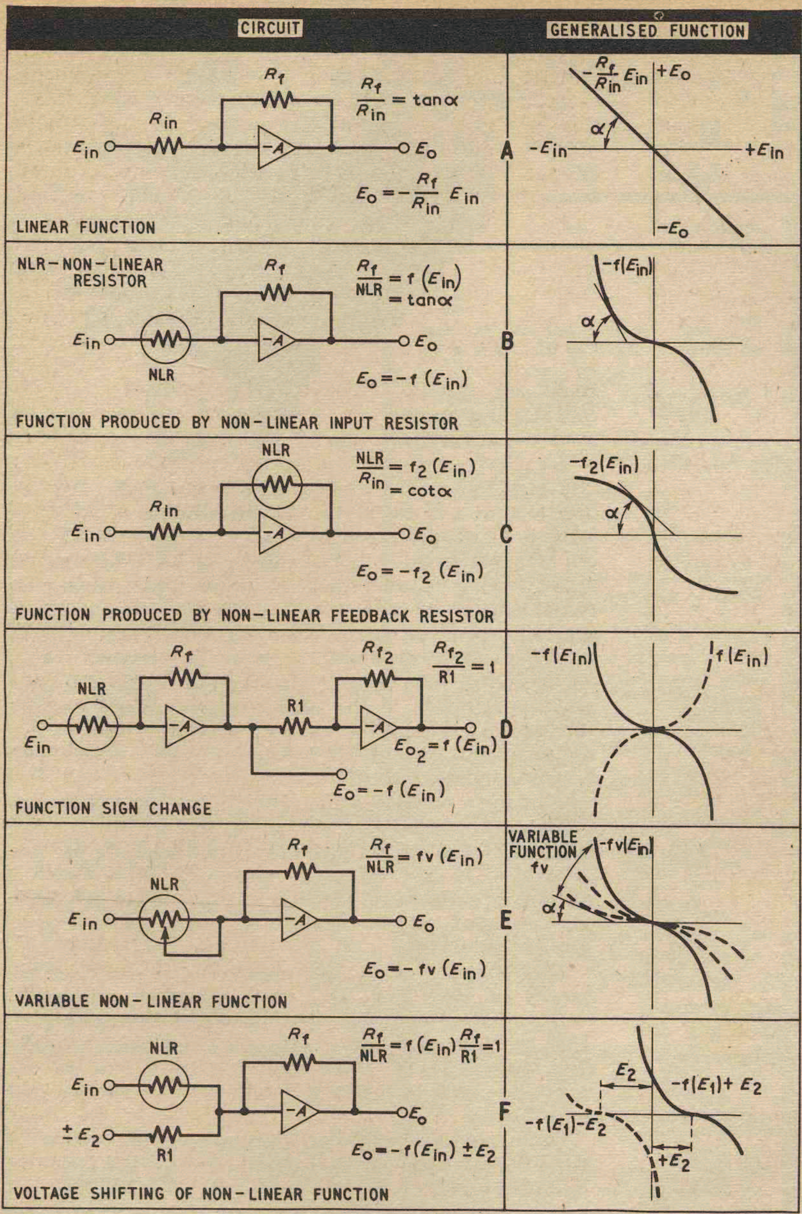


Fig. 7.7. Generating non-linear functions with a voltage dependent resistor

when $t = 0$, and increases linearly to 10ft/sec² when $t = 1$ sec real time. VS1 can be used to adjust the magnitude of a when $t > 0$. Also, if OA1 initial conditions are inserted, in a similar manner to OA2 and OA3, many other time functions of a can be generated.

UNIT "C" FUNCTION GENERATOR

UNIT "C" contains two diode-resistor networks, one for positive input voltages, and the other for negative inputs. The characteristics of each network can be adjusted separately by means of miniature pre-set potentiometers to give a wide range of possible functions, and optimum accuracy. The function generator is designed to be used in place of a normal computing resistor, at the input or in the feedback loop of an operational amplifier.

When employed for squaring an input voltage, with both networks operating in parallel, the function generator will accept input voltages of 0–±10V, and yields amplifier outputs of up to ±10V. Accuracy can be within 2 per cent of the indicated value, depending on the care taken in setting up a function, for input voltages between 0·2V and 9V.

NON-LINEAR FUNCTIONS

Quite often some non-linear function of an applied voltage is needed in analogue computer work, two simple instances being the square or square root of a number. An arbitrary function may also be encountered, perhaps arising from experimental data for which no analytic expression is available.

Servo driven potentiometers and circuits consisting of biased diodes are widely used for generating non-linear functions, but the latter is deservedly popular because it can be adjusted to cater for a range of functions, and does not suffer from a severely limited frequency response.

To show how a diode function generator can give rise to non-linear functions, when allied to operational amplifiers, use is made here of the parallel which exists between the discontinuous behaviour of a biased diode network, and the smooth response of a voltage dependent resistor. Both can display a fall in resistance with an increase in applied voltage.

Consider first of all the circuit and generalised curve of Fig. 7.7a. Input and feedback resistors R_{in} and R_f are not influenced by applied voltage, therefore a straight line function is generated, while amplifier gain and $\tan\alpha$ remains constant. However, if some form of non-linear resistor, or biased diode network, is substituted for R_{in} (NLR in Fig. 7.7b) the gain of the amplifier tends to grow with an increase of E_{in}, and the tangent to the curve will vary according to some function $f(E_{in})$, arising from the characteristic of NLR. A related function $f_2(E_{in})$ results when NLR is exchanged for R_f, as in Fig. 7.7c, but here the amplifier gain falls off with an increase of E_{in}. The curves of Fig. 7.7b and Fig. 7.7c only occupy two of four possible quadrants, but four quadrant operation can be achieved if the function is inverted by a sign changing amplifier, depicted in Fig. 7.7d.

Fig. 7.7e shows how curves, of widely differing slope and magnitude, may be generated if the characteristic of NLR is alterable. Finally, any fixed function will find wider application if its $E_{in} = 0$ datum is shifted, as in Fig. 7.7f. Moreover, as a voltage shift can also be applied to the E_0 axis, it becomes a simple matter to locate any portion of a curve in any quadrant.

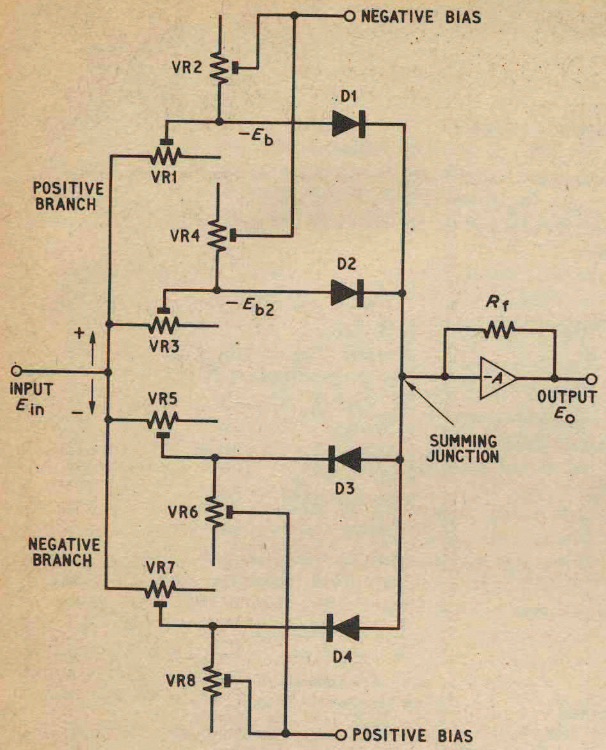


Fig. 7.8a. Circuit of a simple function generator

BIASED DIODE NETWORK

The next step is to see how biased diode networks are used to achieve an increase of resistance with applied voltage, and thus imitate the behaviour of an *ideal* voltage dependent resistor. Unfortunately, currently available silicon carbide, selenium, and copper oxide resistors are far from ideal in many respects, and are not sufficiently accurate for serious use with operational amplifiers.

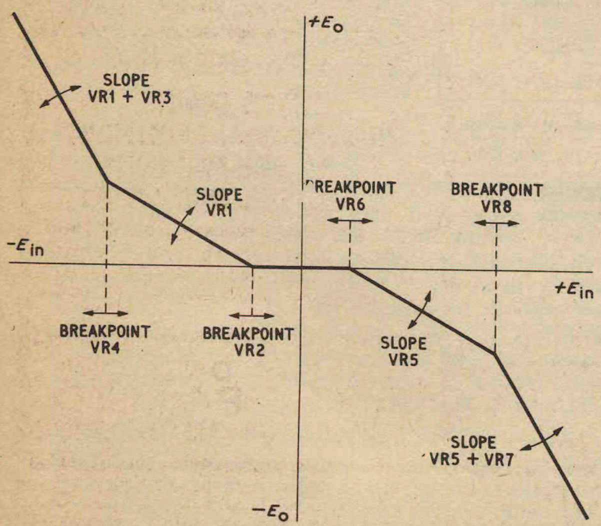
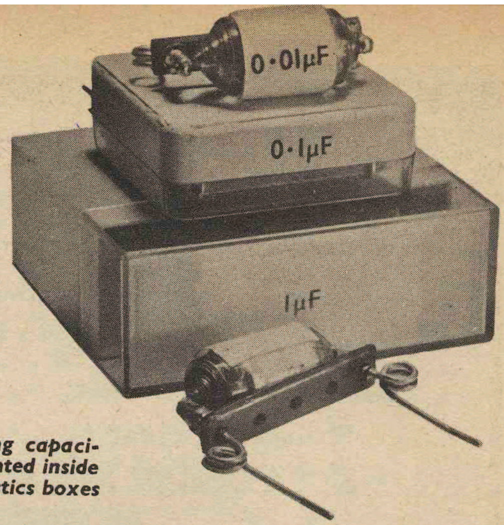


Fig. 7.8b. Adjustable characteristic of simple function generator



Computing capacitors mounted inside small plastics boxes

The UNIT "C" function generator is based on the simple circuit of Fig. 7.8a. In the absence of an input voltage all diodes are biased off, and the network can be represented by a very high value of resistance in series with the operational amplifier input, giving an amplifier gain of almost zero. If a positive voltage is gradually applied to the input terminal, there will be virtually no output until a point is reached where E_{in} is slightly larger than $-E_b$, whereupon D1 conducts and connects VR1 to the operational amplifier summing junction. Further increase of E_{in}, beyond $-E_b$, will produce a straight line output of slope determined by the amplifier gain R_f/VR1.

When E_{in} reaches approximately the level of $-E_{b2}$, D2 conducts and places VR3 in parallel with VR1, thus reducing even more the effective resistance of the network. It can be easily imagined that where a number of diodes and variable resistances are cascaded, the resistance of the network will continue to fall as E_{in} becomes larger still.

Bias voltage $-E_b$ is determined by the relative resistances of VR1 and VR2, and the same applies to $-E_{b2}$, VR3 and VR4. Furthermore, the setting of VR1 will obviously affect the combined slope of VR1 and VR3 (see Fig. 7.8b), and it follows that all the resistance settings associated with D1 and D2 must be interrelated.

Considerations applying to the positive branch of circuit Fig. 7.8a are also pertinent to the negative branch formed by D3 and D4, and VR5–VR8, except that input and bias voltage polarities are reversed. There is no interaction between the resistance settings of the positive branch and the negative branch, and the two can be separated when required for independent use.

The output characteristic curve of Fig. 7.8b identifies slopes and breakpoints with VR1–VR8. As there are only two diodes in each branch, the result is a very rough approximation to a smooth curve. Generally speaking, the accuracy of a diode function generator is proportional to the number of diodes employed, but a natural rounding at the junction of straight lines does occur at low input voltage levels, due to the dynamic resistance of the diodes (not shown in Fig. 7.8b), so the deviation from a smooth curve is not as great as might be expected. Commercial diode function generators sometimes use more than 20 diodes to achieve accuracies of better than 1 per cent.

Next month: Construction of UNIT "C" and some practical applications of this Function Generator.