An Introduction to Analogue Computer Methods

By J. G. Thomason

The modern electronic analogue computer is a set of many individual units of electronic equipment grouped in such a way that provision is made for rapid interconnection of these units to form a specified electrical configuration. By using routine programming techniques it may be arranged that the differential equations obeyed by the voltages in the analogue configuration are identical to those formulated as a mathematical description of a full-scale process. Tests on the analogue may then replace experiment on the process, enabling development to proceed at a greatly accelerated rate. Few advances in the actual techniques of setting up analogues are expected, but considerable fields of application of the technique remain to be explored.

The Analogue Technique

The analogue computer is a set of individual units of equipment, each performing an elementary function, from which may be assembled a physical system which is an analogue of, i.e. has similar properties to, another physical system characterized by limited accessibility for experimentation. The limitation may be either economic, as in the case of experiment on a full-scale production process, technical, as in the case of very small or very large systems, or inherent, as in the case of weapon system assessments. The analogue or model is arranged to obey, in its own set of variables, the equations which have been used to define the full-scale system, and an analogue can only be synthesized, therefore, in cases where a set of defining equations is available; in practice it usually turns out that the derivation of such equations is the major part of an analogue investigation. It is also evident that the analogue can only give results of validity equivalent to the adequacy of the defining equations.

The advantages in having an analogue available for experimentation rather than working with the original system, certainly in the early stages of an investigation, need scarcely be laboured here. Practical, technical, and safety considerations, in addition to the more calculable economic ones, have been appreciated for several years in the aircraft, missile and nuclear power industries, and are slowly becoming accepted in other industries committed to heavy plant investment.

The simplest use to which an analogue is put is the optimization of an existing system. After a series of confirmatory experiments on both the system and its analogue in order to test the validity of the analogue, it is generally a fairly simple matter to search through the permutations of control settings to find an overall optimum. This search may usually be conducted quickly and systematically taking advantage of a faster time-scale on the analogue. This is not, however, the most potent application of the technique. With a flexible analogue it is easy to reconnect to quite different alternative system arrangements, and also to vary parameters normally accepted as fixed by economic or other reasons, as, for example, missile engagement conditions, aircraft performance under engine failure conditions, effectiveness of different sizes of expensive pressure vessels in chemical processes. The basic philosophy has, of course, much in common with that of the scale-model tests conducted by aeronautical and civil engineers.

Though most of what has been said so far applies equally to any type of analogue, whether it be set up using mechanical elements, hydrodynamic circuits, passive electrical circuits, or digital-computer solution of the equations, in practice the validity of the argument depends a great deal on the convenience and ease of operation of the analogue. The modern electronic analogue computer has undergone intensive development in the last five years and now features extreme simplicity and flexibility—advantages which assume very considerable proportions where a computer is intended to be used by various specialist engineers on engineering development projects. The one-to-one correspondence between sections of the original system and sections of the analogue, the visible interconnections between them, and the instantaneous production of pen-records are all very real attractions to the busy engineer who usually very much appreciates any features which facilitate his entry into the world of computer application.

The General Purpose Analogue Computer

The general purpose analogue computer consists of racks of electronic instruments which are the basic building blocks of the configuration which will be connected up to form the analogue. In practice, it turns out that only four basic types of unit are necessary to set up the majority of analogues, and it is the sight of these instruments mounted in groups of up to several hundred identical units which give the larger analogue computers their complex appearance. The connections from every unit are brought to a central area in order that the actual interconnecting wires may be as short as possible. A refinement incorporated on all modern machines is the detachable "patchboard," so that these interconnections may be made (using "cords") on the patchboard whilst it is detached from the machine, thus avoiding tying up the whole machine during what is a separate routine procedure. When "plugged up" the patchboard may then be engaged into the machine, when the plug points protruding through the back of the patchboard will make contact with springs which are the terminations of the wires from the various individual units.

Fig. 1 shows a photograph of an installation of a widely used modern general purpose analogue computer. The patchboard is seen near the centre, plugged into the machine complete with its maze of interconnecting cords. The racks on each side of the central control area contain groups of the basic units. The facilities provided on this type of machine include a digital voltmeter used when setting up the equation coefficients and also for indicating output voltages, a printer for typing out a list of coefficients and outputs, and an eight-channel pen recorder for producing permanent records of up to eight variables simultaneously (not shown).

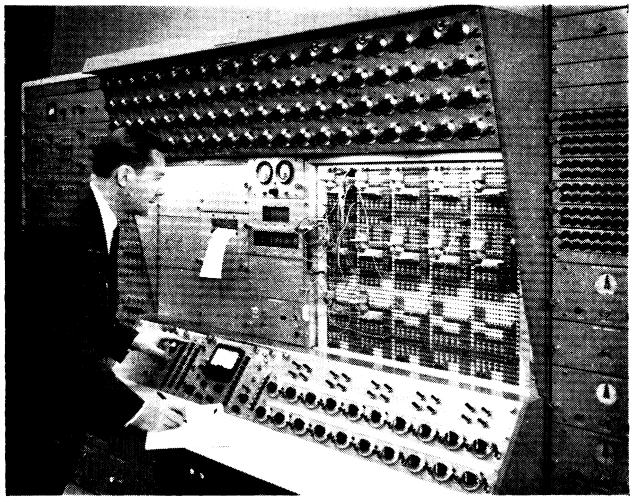

Fig. 1. Example of a modern high-accuracy analogue computer

The Basic Analogue Units

The basic components of the electronic analogue computer are as follows.

The potentiometer. This is used to set into the analogue the numerical value of a coefficient from the equations. A ten-turn helical potentiometer is universally employed and the setting is made by applying 100 volts during adjustment and using the digital voltmeter to read the output voltage. This method is capable of setting to an accuracy of 0·01% and has the advantages that resistor loading of the potentiometer, non-linearity, and dial inaccuracies need not be considered.

The computing amplifier. This is a high-gain amplifier with a frequency response extending from a few hundred cycles per second down to zero (D.C.). The amplifier is used in negative-feedback circuits which enable it very accurately to perform the operations of summing several voltages, or integrating with respect to time the sum of several voltages. Used without a feedback network, the amplifier will always saturate, even with very small input signals, and the sign of the output therefore indicates the sign of the sum of the voltages applied to the input. The amplifier alone may also be used in a derived circuit, as a subsidiary element, as described in the next section. Provision is usually made for the insertion of an initial value when the amplifier is used as an integrator.

The negative-feedback networks used to make the amplifier into a *summer* or an *integrator* are of the type which ensure that the overall performance depends entirely on the properties of the resistors and capacitors and is independent of the amplifier performance if the amplifier gain is infinite. A common value for the gain of a computing amplifier is 10^8, and for all practical purposes the performance of summers and integrators, at frequencies not higher than the bandwidth of the amplifier (a few tens of cycles/sec), may be assumed to be dependent only on the stability of the resistors and capacitors used. In high-accuracy machines, it is found necessary to mount these components in a thermostatically controlled oven in order to minimize the changes due to temperature coefficients and to ageing.

Six separate input connections are usually provided for each summer and integrator, with three of these channels arranged to insert gains of 10. These are used where a coefficient of value between 1 and 10 has to be set in, since the coefficient potentiometer itself is a simple attenuator and can only provide a forward transmission gain between 0 and 1.

The multiplier. In its simplest form, the multiplier is a unit into which are fed two voltages, and which generates an output voltage proportional to their product. Several different all-electronic circuits have been used, accuracies of the order of 0·2% being obtained. A different type of multiplier, particularly favoured in large chemical-engineering studies, is the servomultiplier in which one of the input voltages is used to position the angular setting of a gang of five potentiometers. The first potentiometer is used as part of the servo and the remaining four are available for four separate multiplications or divisions by the first input. The speed of response of the servomultiplier is comparatively low due to the inertia of the moving parts, but the facility for obtaining four operations at little extra cost is attractive in studies where the equations contain many product terms.

The Arbitrary Function Generator. This unit enables a given graphical or tabulated relationship to be set up in the form of a function consisting of several straight-line segments. A 20-segment approximation is commonly used, with perhaps less segments for slowly changing monotonic functions. The unit uses diodes to define the voltages at which each segment is bounded, and is normally termed the *diode function generator* or D.F.G.

The units described above are listed in Fig. 2, showing the commonly accepted symbol for each unit, and the equation defining the operation. Some derived circuits are given, including the *comparator*, which consists of a high-gain amplifier driving a relay, and the *division circuit* using a multiplier as the feed-back element of the high-gain amplifier.

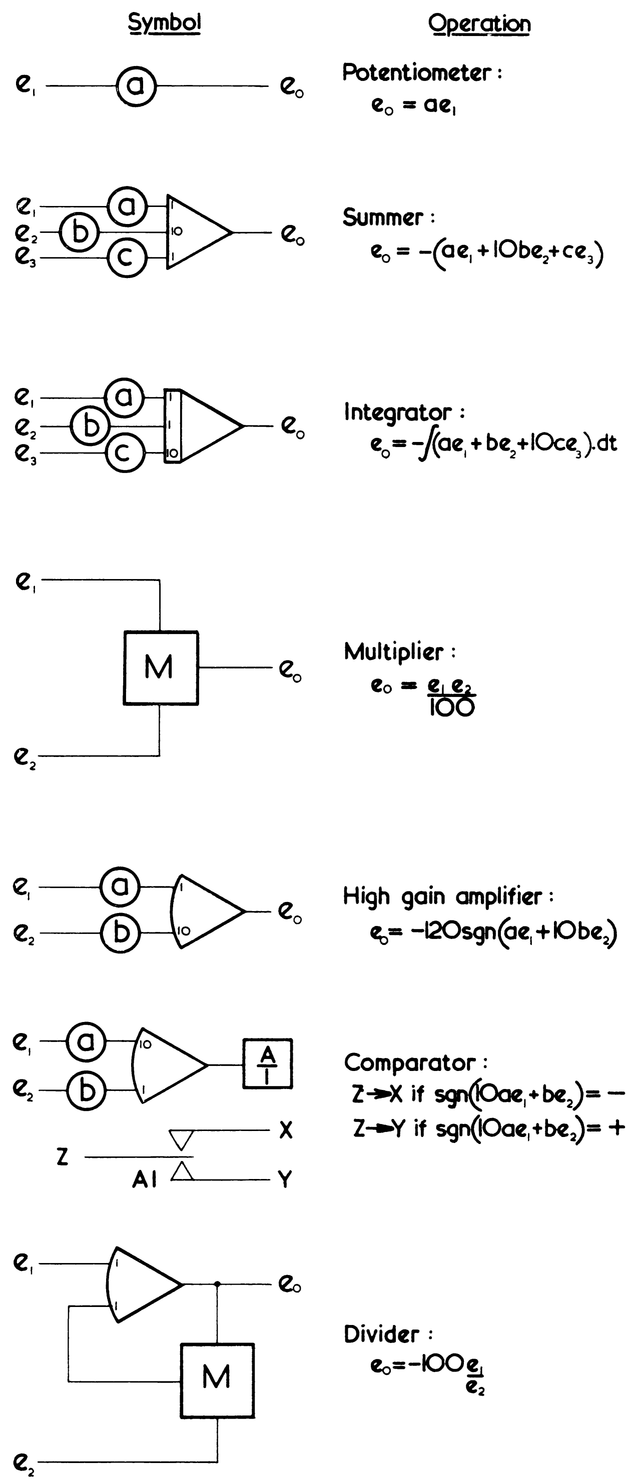

Fig. 2. Analogue symbols and operations

$\left(\text{Note: } sgn\ x = \frac{x}{|x|}\right)$

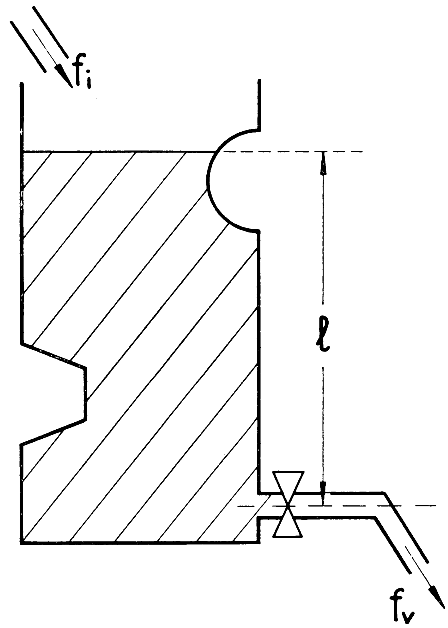

Fig. 3. Irregular-sectioned tank

An Illustrative Analogue Configuration

Fig. 3 shows a diagram of an irregular-sectioned tank which is being supplied with liquid from a hose above and is delivering the liquid via a valve from an outlet near the bottom. It might be required to investigate the variation in level in the tank as the outlet valve is operated and to measure the amount of liquid which spills over the top during transients when the tank is overfilled. Though the analogue of this system is near-trivial, it has, however, the advantage for illustrative purposes that at least one of each of the types of basic unit is required.

A simple set of equations describing the system is:

1. $V = \int (f_i - f_v - f_s)dt.$ (volume accumulation)
2. $l = F(V),$ $l < l_0$ (level arbitrary function of volume)
3. $f_v = k_1(l)^{\frac{1}{2}}$ (Bernouilli law for orifice flow)
4. $f_s = k_2(l - l_0)^{\frac{3}{2}}$ $l > l_0$ (weir flow law for spill-over).

where:

f_i = input flow rate (gal/min),
f_v = rate of flow through the valve (gal/min),
f_s = spillover flow rate (gal/min),
l = liquid level above valve (ft),
l_0 = level of top of tank above valve (ft),
V = volume of liquid corresponding to level l (gal),
k_1 = constant determined by valve aperture and properties of liquid,
k_2 = constant determined by tank top periphery and properties of liquid.

Typical numerical values for, say, a 1,000-gallon water tank might be:

$$l_0 = 8 \text{ ft},$$
$$f_i = 50 \text{ gal/min},$$
$$k_1 = 20 \text{ s}$$
$$k_2 = 10{,}000,$$
$$V\big|_{l=l_0} = 1{,}000 \text{ gal}.$$

The amplitude unit of the computer is the volt, and since all voltages should be kept within the range -100 V to $+100$ V, it will be necessary to insert scaling factors so that scaled variables are generated in the machine. The computer time units are seconds, and in this example it is convenient to write the machine equations in the same time units as those of the original, i.e. minutes in real time will become seconds in machine time. This means that the analogue will run 60 times faster than real time, the 20 min filling time becoming 20 sec on the analogue. Transients may therefore be expected to last about, say, 10 sec, which gives adequate time for accurate response by the servomultiplier and conventional pen-recorder mechanisms. The machine equations, therefore, become

$$[0\cdot 1V] = \int (0\cdot 1[f_i] - 0\cdot 1[f_r] - 0\cdot 1[f_s])dt \qquad (1)$$

$$[101] = \phi[0\cdot 1V] \qquad (2)$$

$$[f_r] = 0\cdot 633\ .\ 10[101]^{\frac{1}{2}} \qquad (3)$$

$$[100(l - l_0)^{\frac{1}{2}}] = 10\left[[10[101] - 10[101_0]\right]^{\frac{1}{2}} \qquad (4a)$$

$$[1{,}000(l - l_0)] = 10\ .\ \frac{[100(l - l_0)^{\frac{1}{2}}][100(l - l_0)^{\frac{1}{2}}]}{100} \qquad (4b)$$

$$[10{,}000(l - l_0)^{\frac{3}{2}}] = 10\ .\ \frac{[1{,}000(l - l_0)][100(l - l_0)^{\frac{1}{2}}]}{100}. \qquad (4c)$$

The arbitrary functions F and ϕ, of course, differ only in scale-factor. A rather exaggerated shape for a tank which is regular except for, say, two restrictions in cross-section at about one-third and two-thirds of the height is shown in Fig. 4.

One possible analogue configuration to investigate the response of this system is shown in Fig. 5. Amplifier No. 1, connected as an integrator, solves equation 1; the arbitrary function generator solves equation 2; amplifier 2, connected as a high gain amplifier, along with the electronic multiplier $M1$, solves equation 3; amplifier 4, connected as a high-gain amplifier, along with servomultiplier $M2$ and three of its associated potentiometers A, B, and C, solves equation 4. Amplifiers 3 and 5, connected as summers, are used to change signs (inverters) and to obtain the required gain over several stages rather than all at one amplifier. The analogue is made to produce responses resulting from varying f_i (supply rate) and k_1 (outlet valve opening), by varying the appropriate potentiometer settings. The time scale is controlled by the integrator time-constant and may be changed either by altering the feedback capacitor (on amplifier 1) or by altering its three input potentiometer settings, all in the same ratio. Note that the potentiometer settings are shown as the four decimal digits as read from the digital voltmeter during setting up, i.e. $0\cdot 1$ is read as 1000.

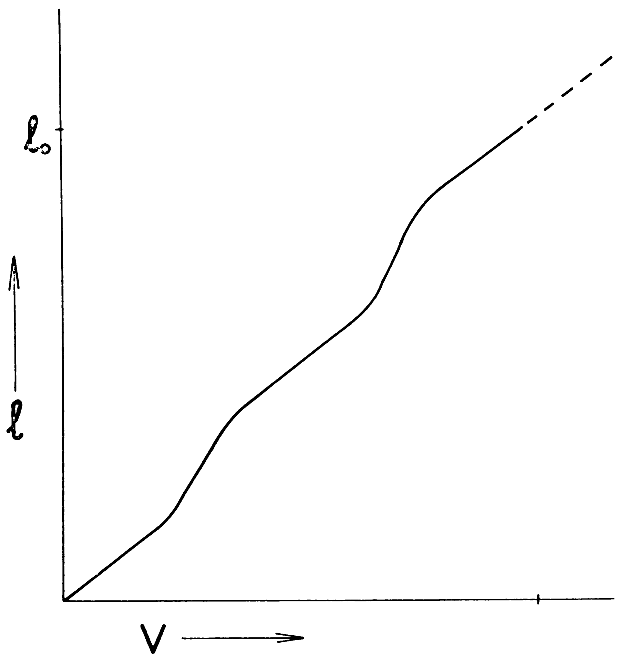

Fig. 4. Tank level-volume relationship

Contemporary Fields of Application of the Analogue Computer

System Dynamics Studies

The simple example of a dynamical problem, used in the previous section to illustrate the programming technique, is also illustrative of the type of differential equation arising in system-dynamics studies. In general there will be several such simultaneous ordinary differential equations, usually of higher order and including a considerable number of cross-terms, non-linearities and variable parameters.

Analysis of records from analogue-computer centres shows that appreciable numbers of problems are encountered where 100 or more amplifiers are used, with a corresponding complement of multipliers (approx. 10%), arbitrary function generators (approx. 5%), and potentiometers (approx. 150%).

The industry currently making the greatest use of the analogue computer is the nuclear power industry. In particular, considerable effort is being devoted to analogue studies of reactor start-up and controllability. Aircraft stability and wing flutter problems were amongst the first to be set up on an analogue computer and are

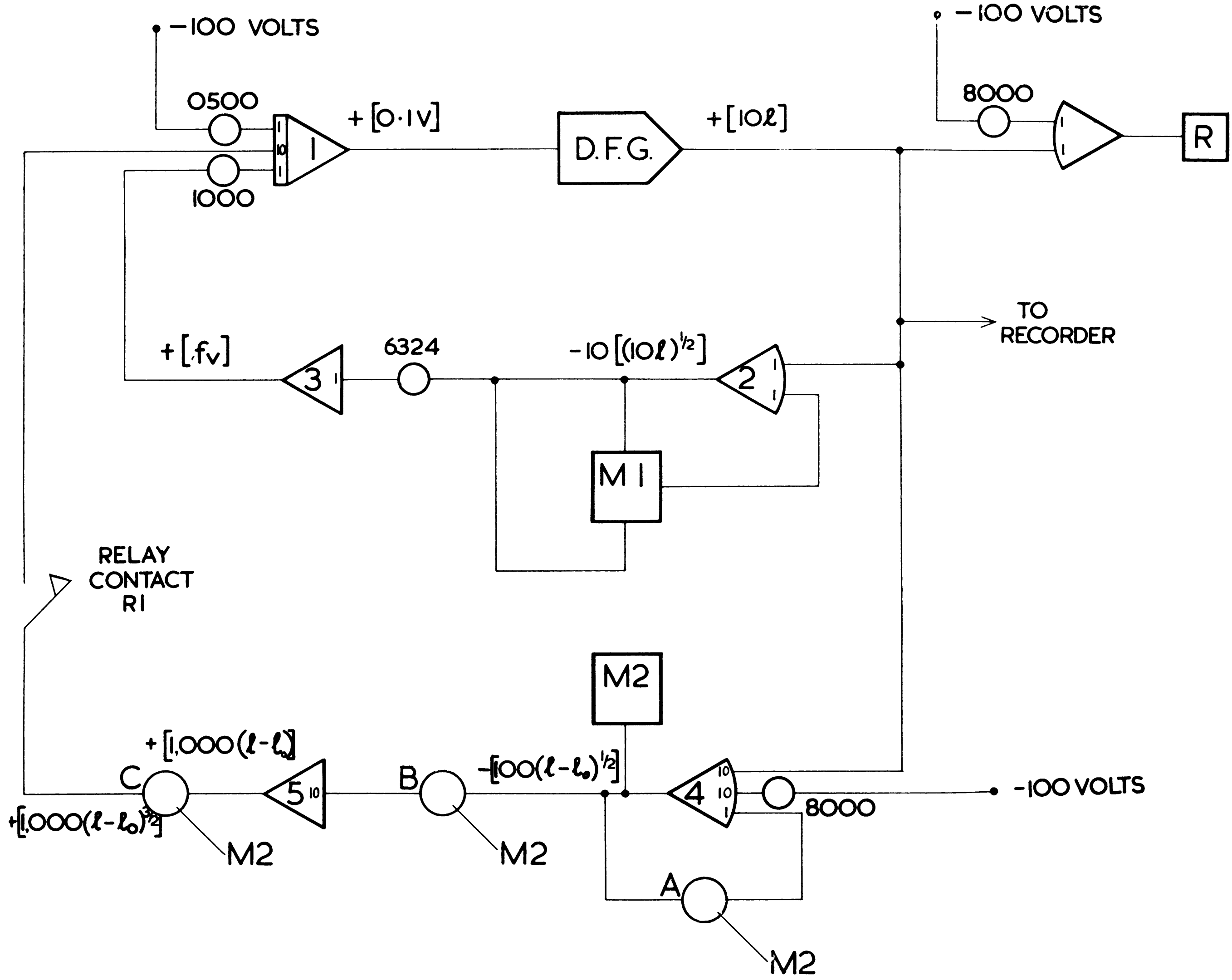

Fig. 5. Analogue configuration corresponding to equations 1–4

still actively studied. In the missile field, analogue studies of missile performance are made at all stages of the development, from individual actuation units to assessment of a complete defence system in a tactical situation. For example, control surfaces which are actuated by pneumatic or hydraulic motors are part of a servo loop, and such complex servos are commonly very non-linear, cross-coupled, and have parameters which vary with altitude incidence, velocity, etc. The controllability and manœuvrability of the complete missile involves study of the coupling between the homing or guidance systems and the actuators, and assessment of the overall performance of the missile in a tactical situation will have to include also the effects of target evasion, random disturbances, etc.

In the field of process dynamics and control, where the process itself can be adequately represented as a combination of lags and delays, the general run of differential equations is similar, mathematically, to that arising in the other fields mentioned. In several investigations, however, a more realistic approximation must be made to the partial differential equations which describe such phenomena as heat transfer, etc. The technique currently adopted in such cases is to approximate each partial differential equation by a set of differential difference equations, choosing the number of cells more or less intuitively after consideration of the time-constants of any lags or delays following the spatial process in the control loop. A commonly used number of cells is five. Control systems investigated have included those for: evaporators, coal- and oil-fired boilers, turbines, level controllers, autoclave temperature regulators, chemical composition regulators (e.g. pH control), etc. etc. Chemical kinetic equations have been set up for the rates of the actual reactions themselves, these programs in general requiring an extremely high proportion of multipliers due to the preponderance of square terms and cross-products, each with a coefficient which may be a function of temperature, pressure, etc. Activation energy curves may be set up on diode function generators.

Experience with the control studies has shown that the engineers very much appreciate having the analogue at their finger tips, implying freedom to make changes which were not anticipated at the programming stage. The chemical kinetics studies have obtained less differential benefit compared with, say, digital-computer solution, in some cases where detailed examination of the one output function was the aim, rather than a flexible search for basic mechanisms. However, in one particular analogue study of a tubular reactor which had heating and cooling sections, a useful optimization of heater powers and dispositions to give a maximum product yield to side-reaction ratio was performed in the course of a few days.

System Simulators for Training Purposes

The potential value of the analogue for training purposes was realized by users of aircraft many years ago, and within the last ten years considerable numbers of very highly refined aircraft trainers have been produced for civilian and military use. The realism of these trainers, which are usually valued at £¼M. each, is carried to the degree where the trainers may be used for pilot and crew assessment. The analogue circuit, which performs the mathematical operations equivalent to the dynamics of the aircraft in flight, is usually of about 300-amplifier complement.

More recently, the nuclear power industries have ordered power-station operator training analogues, so that operators can become familiar with routine and emergency control whilst the actual power station is still under construction, so that, right from the initial start-up, trained operators are available.

Analogues of complete early-warning and strategic defence control systems are available for training radar operators, provision being made for the insertion of a set of signals representing a full-scale attack which may be intercepted only if appropriate decisions are made quickly enough, based on the information presented by the radar equipment.

In all these simulators, great care is taken to ensure that the realism is as complete as possible. The controls, meters, recorders, etc., are of the same type as those used on the real system, though it is usually necessary either to modify these instruments internally so that they will provide and operate on electrical signals, or to use external transducers. All such analogues, of course, are designed to run in real time (1:1 time-scale) and, where high accuracy is required over long periods, as in aircraft navigation simulations, the amplifier-type integrator is usually replaced by an electro-mechanical integrator, since the usual integration formed from the computing amplifier has a slow drift which can become appreciable after a run lasting over about an hour. It may be of interest to note, for comparison, that as a rough guide, contemporary digital computers are not fast enough by a factor of the order of 100 to be used in these large real-time simulations.

Application to Economics

Though the principles involved in making fairly comprehensive calculations concerned with expected returns from capital investment are quite well known, little use has been made of them in the past due to the prohibitive amount of time required for manual computation. During the last two or three years, however, experiments have been started in order to assess the usefulness of the analogue computer in this field. The choice of analogue computer was influenced by the user requirement that a clear graphical display should be produced virtually instantaneously after resetting a coefficient.

It is known that experiments are proceeding along these lines in the U.S.A., and at least one machine has been reported in the U.K. (see ref. 48). This latter machine based the calculation of returns on the "present-worth" concept, using the formula

$$P_x = \frac{x}{(1 + i)^n}$$

where P_x = present worth of £x payable or due after n years, at a rate of interest $100i\%$. Results produced showed good agreement with manual computation checks—a specimen record is shown in Fig. 6.

Operations Research

This is another field where investigations into the application of analogue computers have been seriously considered only during the last few years. In engineering investigations it has become quite commonplace for studies to include the effect of injecting random disturbances into the analogue. The *noise generator* is a standard item of analogue-computer peripheral equipment, the better designed units producing one or more channels of uncorrelated random noise at about 5 volts r.m.s. with Gaussian amplitude distribution and a power spectrum which is level from zero to a cut-off frequency usually of about 20 c/sec. Assessments in terms of the conventional mean-square error criterion are readily made by using the standard computer units to program the required modulus generation, squaring, and integration. In this type of study the analogue is allowed to operate continuously for a fixed time, after which the error integrator level is recorded. This process is often extremely tedious to run, even at the high speeds available by analogue-computer techniques, and at least one

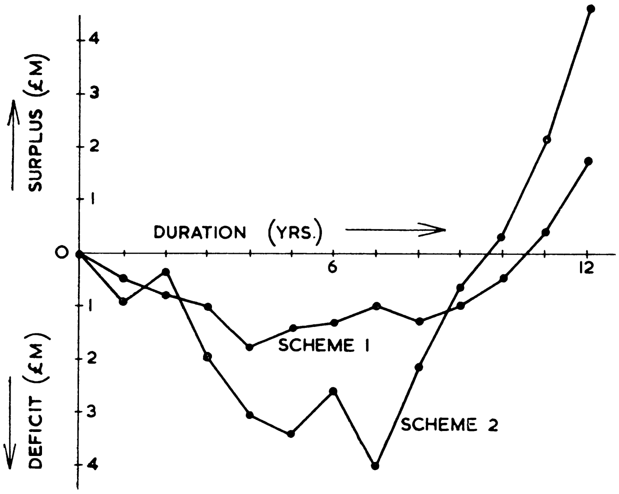

Fig. 6. Piofitability-Life computation

machine incorporating automatic operation and recording has been reported in the U.K. (see ref. 38).

Organization problems are not readily studied on the analogue computer, due to its inability to store information and the clumsiness resulting when too many of the standard comparators are used in decision-making circuits. However, there are assurances that new machines will shortly be offered with associated storage facilities using magnetic tape, and it is expected that this innovation will greatly accelerate the application of the analogue method in this field.

Several reports on successful linear-programming studies using analogue computers have been reported and, again, the advantages of the facility to see quickly the effects of a change in each restraint has been praised as a major attraction of the machine. It has been pointed out, also, that the extension to non-linear programming, whilst necessitating multipliers and function generators, will not significantly reduce the speed of solution, and the possibility of applications in this field is under investigation by computer applications engineers both in the U.S.A. and the U.K.

An important study in this last field is power dispatching from a network of power stations feeding a grid network. An analogue representation of this situation has been set up and automatic optimizer systems tested, these dictating the required power generation level at each station in response to fluctuating loads at the various consumer areas, where the optimizer is programmed to secure minimum transmission losses.

Conclusions

The modern general purpose electronic analogue computer presents a technique for the rapid construction of analogue models. The programming is simple and flexible, and a 1:1 correspondence between units in the full-scale process and units in the computing machine is retained. The computing speed is generally fixed by the machine at about 5 seconds to produce one complete transient, necessitating either slowing down or speeding up the computer time-scale. A variety of stimuli and disturbances may readily be injected, and waveforms at any intermediate point in the process may be viewed or recorded. Major changes in coefficient settings or configuration may be made quickly. Where pen-recordings are not required, solutions may be produced repetitively at a rate of up to 100 per second, with response waveforms displayed on a cathode-ray oscillograph.

It is found that these characteristics often appeal to engineers rather more than do the prospects of, say, having to learn how to program a digital machine, even by means of an autocode, and obtain results from subsequent postal exchanges with a digital-computer service centre. As a first introduction to the use of the process model technique, evidence is accruing to suggest an initial approach being made through an analogue computer, as it is during the early stages of formulation of the equations describing a process that the rapid system-change facilities of the analogue computer have proved most useful. At the end of this "evolutionary" phase, when the set of equations has been finalized and there is no longer interest in the mechanism of solution, it is usually recommended that the solutions to be used in actual design work be obtained by arranging for the equations to be handled by a specialist mathematical section, using a digital computer in order to utilize the high accuracy obtainable with digital techniques.

Two disadvantages of analogue computers are their inability to store information, incidentally making accurate simulation of true delay (or D/V lag) difficult, and secondly, the limitations imposed by amplifier stability when an attempt is made to use the machine to solve ill-conditioned simultaneous algebraic equations. The accuracy of the best contemporary machines is 0·01% per operation, and this is unlikely to be improved, due to the limitations imposed by the physical properties of the capacitors and resistors used in the feedback net works, i.e. hysteresis, dielectric adsorption, ageing, etc.

Developments in machine performance are likely to occur in the field of automatic setting up as larger machines come into service. Most manufacturers of large machines offer, as an extra, a unit which will set the coefficient potentiometers from a paper tape program. Automatic patching systems similarly programmed are known to be under development in the U.K., and a demonstration of an economic system is awaited. A variety of delay simulators are also at the development stage, but experience with the different units has not yet been sufficient to make a comprehensive assessment from the range of systems, which includes: magnetic-tape recorders using A.M., F.M., or digital signals, magnetic drum with flux-gate heads, rotating capacitor drum, etc.

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Book Reviews

Computer Engineering. Edited by S. A. LEBEDEV, 1960; 184 pages. (Oxford: Pergamon Press Ltd., 63s. 0d.)

This book contains eight papers on some aspects of computer engineering in U.S.S.R. translated into English. The references quoted by these papers are not later than 1956, which makes the book something of a "period piece." In view of the rapid strides in computer technology since that date, both inside U.S.S.R. and elsewhere, the interest of the book is historical rather than technical.

The first paper deals with power supplies for the original BESM machine and deals with regulation and also marginal checking by variation of filament supplies. There follows a long paper of 74 pages on Digital Differential Analysers which is almost entirely a review article of U.S.A. practice. No less than 21 out of 22 references are to U.S.A. publications!

Next appears a very good account of "Dynamic Flip-Flops and their Use in Parallel Action Computers." This extends over 38 pages and is quite stimulating. Interesting applications are shown for frequencies up to 1 Mc/s. Naturally, this is entirely based on thermionic valves and not transistors.

The remaining papers are shorter and deal with a form of parity checking in a serial arithmetic unit; dictionary look-up for mechanical translation; properties of ferrite cores for coincident current and word selection stores; and a glossary of technical terms. There is nothing novel in these papers and comparable information is readily available in the usual scientific and technical journals.

There are a few small misprints, particularly among the references, but these will not mislead any historians of computers.

P. TAYLOR.

Sampling Methods for Censuses and Surveys, by FRANK YATES, 1960; 440 pages. (London: Charles Griffin & Co. Ltd., 54s. 0d.)

This is the third edition of a very successful and well known book by the President of the Society. The subject-matter of the book is well described by the title; it is not a treatise on mathematical statistics, but is intended as a manual for those who plan and carry out censuses and statistical surveys of various kinds. The author has primarily in mind surveys of an official or scientific character. The same statistical principles apply, however, to opinion polls and surveys conducted for the purpose of market research, and the book will be of general interest to those engaged in these subjects. A perusal of the less technical parts of the book would also be profitable for those on whose behalf market research surveys are undertaken; they would then understand that it is not as simple as it sounds to obtain reliable information by sampling, and that if results are to be obtained quickly and cheaply some risk must be taken of introducing bias into the sampling.

Earlier editions of the book contained sections on the use of Hollerith punched-card equipment for census and survey work, and the author has now added a chapter on the use of electronic computers. This will be useful in drawing the attention of practical statisticians to the advantages that can be obtained from the use of computers, both in the reduction and in the critical evaluation of data. A section on the editing of data with the aid of a digital computer is of special interest. Those who have not been concerned with data reduction, whether the data arise from statistical surveys or from scientific experiments, may not realize how important this is. Any large body of data is bound to contain errors and inconsistencies and these must be taken care of by the machine, at machine speed, if a bottle-neck is not to arise. The machine must be programmed so as to subject the data to a close scrutiny, and to reject, correct, or refer for future examination, any which fail to pass the tests. In cases where some rejection of data may be necessary there is a distinct advantage in having it done by a program rather than by a human being, since the machine can be trusted to apply the rules impartially, and, if it is later suspected that bias has been introduced, an examination of the program will reveal the exact nature of the criteria that were used.

The critical analysis of results calls for much computation. Most of the procedures used are straightforward in themselves, but the necessity of developing approximate methods which could be applied without excessive labour has in the past tended to confuse and complicate them. The coming into wide-spread use of digital computers should enable many sources of mystery to the uninitiated to be removed.

M. V. WILKES.