AUTOMATIC CONTROL SYSTEMS

By Prof. A. TUSTIN
University of Birmingham

AUTOMATIC control was the subject of a paper in Section G (Engineering) of the British Association at this year's meeting at Birmingham. It has since been the theme of a very well-attended conference at the University of Birmingham, and next year (July 16–21) it is to be the topic of a conference which is being arranged by the Department of Scientific and Industrial Research. The interest in the subject is world-wide, and is not confined to professional engineers.

This spate of interest and activity, like most spring tides, is due to a conjunction of causes. War-time developments such as automatic aircraft tracking, the guiding of flying-bombs, automatic gun-laying and many others led to a clearer understanding of what was possible, and suggested many industrial applications of the same principles.

New possibilities have been opened up by progress in developments of thermionic amplifiers, and the theory of amplifiers and filters, and by the appearance during recent years of a series of new forms of amplifier for larger powers. These include many varieties of rotary amplifier, such as the 'metadyne', the 'amplidyne', the 'rototrol' and the 'magnavolt'. There is also the magnetic amplifier—a development of the saturable reactor—and various controlled gas-discharge devices, such as the 'thyratron' and the grid-controlled rectifier.

A good deal of the present interest in automatic control arises from the fact that specialists in every branch of industry are asking whether some particular process can be done better under automatic control than under human control. They sometimes ask whether automatic control may make possible a precision and speed which no human operator could approach.

The recent developments in automatic control have been of interest to many scientific workers outside the field of engineering because of certain very striking analogies, and in a limited sense identity of principle, between the engineers' 'closed sequence controls' and a variety of phenomena in physiology, neurology, biology and economics which are somewhat analogous to 'situations of control', and which are characterized by the occurrence of oscillatory variations or instability.

The concept which has clarified the engineers' approach to control problems, and which is equally applicable to this wide range of phenomena in other fields, is that of a 'closed sequence of dependence'. In seeking to describe the behaviour of any system, one may characterize its state by the values of a number of quantities or variables. The equations describing the system state how the value of each variable is determined by one or more of the other variables. It is very illuminating to represent the 'scheme of dependence' diagrammatically as in Fig. 1. Here various interdependent quantities in a system are represented by the circles; and a line with an arrow, from B to C, for example, means that C is dependent on B, and alongside this arrow may be indicated (by the equation or an equivalent operational symbol) how the variation of the quantities are related. Such a diagram is simply a particular way of writing down the set of equations of the system. It makes visible

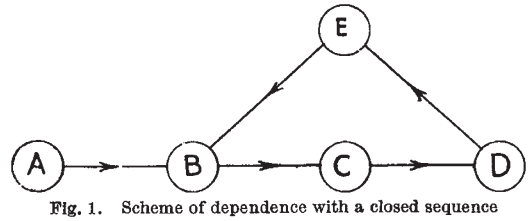

Fig. 1. Scheme of dependence with a closed sequence

a distinction which is of great importance in respect to the behaviour of such systems, namely, the existence or non-existence of any 'closed sequence of dependence', such as the sequence B–C–D–E–B in Fig. 1.

The significance of this distinction is that systems the scheme of dependence of which includes one or more closed sequences are liable to show various forms of 'self-excitation'. If the quantity B in Fig. 1, on increasing, causes, via the closed sequence, and subject to some time delay, an increase in B, then the behaviour of the system may, on certain conditions, be a sustained or cumulative increase in the value B. A kitten chasing its own tail is a good example of such a closed sequence system. We do not know what mathematical function would best describe the dependence of the activation of the kitten on the proximity and velocity of the tail; but the rate of gyration has been observed to rise to a considerable value, no doubt limited on account of the non-linearity of this dependence.

If, on the other hand, the response or 'feedback' via the closed sequence is not positive (or cumulative) but suppressive, self-excitation is still possible if this response is delayed in time; but in this case it is oscillatory, at such a frequency that the feedback is delayed in phase by 180°, and so is cumulative at that frequency.

Most control and regulating devices have 'schemes of dependence' of the same basic pattern as that given as Fig. 1, because they are 'error actuated' systems. For example, consider the auto-pilot of an aircraft. A device is provided that 'measures' the error ε of direction of flight from a required angle θ_i (relative to the axis of a gyro-compass). If the direction of flight is θ_0 then $\varepsilon = \theta_i - \theta_0$. The error ε is caused to determine the angle of the rudder, which in turn determines the rate of turn of the aircraft, and so determines the variation of θ_0; and the direction of variation is, of course, made corrective. The basic 'scheme of dependence' is then as shown in Fig. 2.

The arrows from ε to θ_r and from θ_r to θ_0 represent respectively the dependence of rudder angle on the error, and the dependence of direction of flight on rudder angle. Both these dependences involve time-lags, and the closed loop is suppressive. Thus the system is capable of self-oscillation if the response round the closed loop is sufficiently great at the

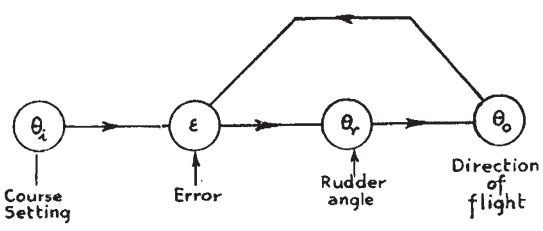

Fig. 2. Scheme of dependence for an automatic pilot

frequency at which the phase-lag is 180°. This sets a limit to the accuracy of control possible. Time-delays in the response of the 'control sequence' are the enemy of accurate control.

Present developments in automatic control largely centre around the search for means of amplifying power without undue time-delay. The thermionic amplifier is ideal for low-power stages, for its time-delays, in this context, are negligible. The high-power stages must, however, provide the required output, and in some applications, such as varying the 'draw' or tension in a steel-rolling mill, hundreds or even thousands of horse-power may be required. No means has yet been devised of obtaining continuous control of large powers which is instantly responsive to control signals of small power. These time-delays are usually due to storage of energy in the apparatus corresponding with each increase in output, and obviously such energies cannot in practice be built up instantly when some low-power input quantity changes, because such an instantaneous change would imply an infinite source of power. To a limited extent these supplementary energies may be supplied from the output or high-power end of the sequence, and this is the basis for the use of 'supplementary feedsback'; but the possibility of such further closed loops introducing new problems of stability will be obvious.

The occurrence of such closed sequences of dependence in many fields outside engineering would be expected. In the neuro-muscular systems of animals many examples occur. Derangement of such systems may produce characteristic oscillatory phenomena, such as tremors, or that periodic variation of breathing-rate known as Cheyne–Stokes respiration. In biology, the oscillations of competing populations may be described in this way. In economics, J. M. Keynes displayed the mechanism of the economic system as that of a closed-loop system, although he did not use this term. The principal closed sequence is: level of incomes – expectation of profit – rate of investment – level of incomes. There is also a sequence of higher periodicity, namely, income – spending – production of consumption goods – income. Economists now appear to accept the general implications of this closed-sequence situation, and the implementation of a full-employment policy largely depends on this recognition; but they appear to find difficulty in discovering, by field-studies or otherwise, the essential data relating to the time-functions involved in these dependences. If they could suggest possible forms for these time functions, electronic models could easily be contrived that would simulate the behaviour of an economic system for which they applied.

An advantage of recognizing the significance of closed sequences of dependence wherever they occur is that such recognition immediately makes available all the apparatus of analysis that has been built up around the engineer's problems, including the feedback amplifier. Particularly in the case in which the dependences, for some range of variation, are approximately linear, a great wealth of mathematical apparatus exists, which provides the answer to almost all questions likely to be of interest. Even when non-linear relations are involved, both useful methods of attack and a few useful general results are available, and in all cases, however complex, there are possibilities of semi-experimental investigation using electronic or other analogues. It is to be hoped that teachers of physics, mathematics and engineering will pay more attention to the concept of the closed sequence and its implications, not only because of its already very great importance in many fields of technology, but also because it provides an excellent example of a concept extending over a very wide range of phenomena, and provides a simple approach to many topics in applied mathematics, which is of pedagogic value.

There are two aspects of the study of closed-sequence systems which should be specially mentioned, because they are being actively investigated at the present time. The first is the application of automatic control in the chemical industry, and the control of chemical processes by measurement of physical quantities that indicate the state of material undergoing continuous processing, and regulation of temperature, flow, pressure and so on in accordance with these measurements. This field has its special difficulties because of the very long response-delays involved, and because of non-linearities in the response characteristics. A second field of present importance, in relation to defence as well as to industrial problems, is the behaviour of control which involves a human operator, that is, manual control. This situation involves a closed sequence via the dependence of the action of the operator on the quantities (meter readings or other indications) which he receives. As such responses, even of a highly trained operator, involve irreducible time-delays, the possible accuracy of manual control is limited. This situation arises, for example, in the control of high-speed aircraft from instruments, or in the laying of a telescope on a moving target. There is great interest in the processes by which, in the course of training, well-determined patterns of response are developed, and it may be expected that progress will emerge from such studies both in improvement of training methods and in the improvement of control characteristics.

BRITISH EMPIRE CANCER CAMPAIGN

ANNUAL REPORT FOR 1949

THE twenty-seventh annual report of the British Empire Cancer Campaign* is a substantial volume of 363 pages, giving an account of the biological, chemical, physical and clinical investigations supported by the funds of the Campaign (including administration and appeals, £212,000 were disposed of in 1949). No single reviewer could adequately deal with all four categories of research; moreover, compression and selection in this article, dictated by limitation of space, will leave many interesting topics unmentioned.

The rank growth of some lines of cancer investigation, particularly on the carcinogens and on tumour inhibitors, has rapidly led from discovery to the developmental phase, where a considerable proportion of the publications describe detailed methodical variations of conventional types of experiment. Interest has been stimulated by the introduction of modern physico-chemical theory in studying the relation of structure to activity of carcinogens and tumour inhibitors. The section of the report dealing

* British Empire Cancer Campaign. Twenty-seventh Annual Report covering the Year 1949. Edited by Sir Heneage Ogilvie. Pp. 363. (11 Grosvenor Crescent, London, W.1. 1950.)