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THE DEVELOPMENT OF CONTROL IN THE PROCESS INDUSTRY

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Synopsis This paper traces the evolution of the theoretical basis of automatic control. The subject is considered from the viewpoint of applications in the process industries, particularly those occurring in papermaking. The emphasis is put on the essential concepts, placing them in the general background of engineering systems analysis. An attempt is made to indicate the mainstream of theoretical developments and to review current practice and the future potential of control technology in the paper industry.

Introduction

TWENTY years ago, there was a small band of enthusiasts who were interested in control engineering. Today, it has become a major discipline with large departments in most of our universities. The majority of engineering undergraduates are exposed to the basic principles and many higher degree courses are offered. This explosive growth has opened up a large number of pathways stimulated by a wide variety of potential applications. There has been intensive work on the theoretical front, with a great deal of interest being taken by people with a strong mathematical background.

This paper will attempt to survey these activities and try to indicate the main stream of development as it is relevant to the control of industrial processes such as those found in the papermaking industry. In retrospect, it is possible to identify certain critical developments and to learn some lessons from some of the disappointments. This will help also to put the subject into the perspective of the general pattern of engineering analysis.

The essential characteristic of the systems in which we are interested is their dynamic behaviour. This means that they change their state in time owing to changes in their inputs. Some of these will be intentionally applied and some will arise from naturally occurring disturbances. The whole system is made up of many interconnected elements, which respond together to form a simultaneous dynamic system. Typically, such components represent the accumu-

Under the chairmanship of N. C. Underwood lation and delay of material, energy, heat, momentum or, indeed, of quantities such as information or cash.

Our main interest in these systems lies in the outputs. These are the variables that are regarded as characterising the final state of the product. One further set of variables is important—these inputs over which there is some control and that can be adjusted from time to time. The control problem consists of finding a means of varying the control inputs so that the outputs behave in some desirable way, despite the variations and disturbances that enter the system. The most basic problem in process control is that of continuous regulation. A regulator is a control scheme for maintaining the outputs at constant levels.

One common form of controller that is widely found and is most effective is man. Many plants are under manual control and, in the higher levels of control (which are usually called management), the human operator certainly dominates. There are two primary components to the control problem. In the first place, there is the inherent dynamic nature of the system. If significant changes occur on the time scale of seconds, man finds the task very difficult. If, on the other hand, the time scale is hours or weeks, then man is much more able to cope with the situation. Secondly, there are the difficulties that arise from the complex interconnection of real systems. In this area, man can score heavily with his special pattern recognition abilities, so long as the changes are slow enough for him to keep track of them. Thus, it is not as surprising as it may appear at first sight that manual control is still to be found right down the line from the financial comptroller of the corporation to the plant operative making adjustments to flows in the machine.

Early automatic controllers

MEN soon became bored with controlling simple pieces of equipment, particularly if their time scale was rather on the short side. The conceptual breakthrough came with recognition of the principle of feedback. The idea is to take a measure of the output of a system and compare this with the desired output. The difference forms an error signal that, in turn, adjusts the controlled input. If there is no error, there is no control action; the greater the error, the

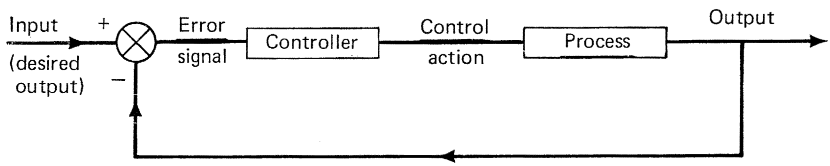

Fig. 1

greater the action. The sign of the error must be negative so that the control action will tend to counter rather than reinforce discrepancies in the output. This idea can be illustrated diagrammatically for a simple system with one input and one output (Fig. 1).

The early applications of this idea were engine governors, of which the best known is Watt's flyball speed regulator for his steam engines. There were many ingenious improvements of the engine governor, which were developed empirically. It soon became apparent that it was all too easy for such feedback systems to be unstable, exhibiting uncontrollable oscillations known as hunting.

In 1868, Maxwell published an epic paper in the *Proceedings of the Royal Society of London*, in which he gave the first theoretical analysis of feedback regulators. He described the dynamic behaviour of such systems by time-dependent differential equations. By assuming only small local disturbances, he could linearise the equations. He was able to show that for certain systems it was possible to identify which conditions would lead to unstable oscillatory behaviour. Unfortunately, no one took up his recommendation to continue these investigations and it was nearly half a century before the theoretical study of control systems was resumed.

There was another important development that occurred between the wars. A bulk chemical industry was evolving and it became imperative to develop simple cheap devices that could regulate such variables as flow, pressure and temperature in these plants. Such controllers were applied to local points in the plant. The medium of information flow was air pressure and the device that evolved was the pneumatic three-term controller. This consists of arrangements of bellows, nozzles and levers with three external controls. By suitable adjustments, these could cope with a relatively wide range of time scale and a considerable range of dynamic characteristics. These controllers remain today the most widespread control devices and they have held their ground in the face of many alternative approaches.

Communications engineering

THERE was another area of activity in which control ideas became important. As the science of communication grew, the need arose for the design of better amplifiers and networks to carry speech signals. The Bell System's laboratory pioneered the theoretical study of these problems and gave rise to the first properly formulated theory of control systems. The chemical industry was concerned with time behaviour of their systems, but the communications industry was interested in the way in which networks attenuated the frequency characteristics of speech signals.

By the turn of the century, Heaviside had pioneered the use of an operational calculus for electrical network analysis. He showed that systems of ordinary differential equations (mathematical models of the networks) could be much more simply handled by introducing a differential operator. This reduced them to ordinary algebraic equations. The important advantage came when complex systems were built up from subsystems. The process of interconnecting became one of simple algebraic manipulation. If two systems are joined in series, the equivalent operation is to multiply their transforms. In this way, a very complicated system could be built up and studied by modelling the subsystems and operating on their transforms.

Earlier, Laplace had worked on an integral transform that was very similar to Heaviside's, but slightly more convenient to use. At the Bell laboratory, they discovered that this Laplace transformation of the equations could yield the frequency behaviour of the system by simply substituting a complex variable for the Laplace operator. Thus, a frequency domain characterisation of an entire system could be obtained by carrying out the following steps—

1. Model the elements of the system as ordinary linear differential equations.
2. Transform the element equations by the Laplace transform.
3. Interconnect the system by multiplying the transforms of those elements that are connected in series.
4. Substitute a complex variable for the Laplace operator.
5. The modulus of this expression then gives the amplitude/frequency characteristic and the argument gives the phase/frequency characteristic.
6. If the time behaviour is required, then the final Laplace transform must be inverted. This is by no means always a simple matter.

Once this concept of the frequency domain was established, two other vital steps could be taken. Nyquist was able to deduce a simple graphical criterion that established whether or not a system was inherently stable. He generalised the work that Maxwell had started 64 years earlier. At about the same time, Bode was able to present the first steps in the systematic synthesis of controllers to improve entire system performance. The method was semi-graphical and was based on the physical insight into the general behaviour of a system, which would be read into the frequency characteristics.

Thus, by the mid-thirties, there was a real body of theory with which to attack the control of dynamic systems. With this theory, it is now possible to analyse the ubiquitous three-term controller and uncover some of its inherent strengths.

The three-term controller

THE actual mechanics of this device is fairly complex, but it can reasonably be approximated to the following—

$$\theta_0(t) = K_p\left[\theta(t)+\frac{1}{T_i}\int\theta(t)dt+T_d\frac{d\theta}{dt}\right]$$

where $\theta_0(t)$ = output signal
$\theta_0(t)$ = error signal (input to the controller)
K_p = proportional gain
T_i = integral time
T_d = derivative time.

In the physical device, it is possible to adjust the three constants K_p, T_i and T_d.

If this equation is reorganised, it becomes—

$$\theta_0(t) = \left[K_1 + K_2 \int dt \times K_3 \frac{d}{dt}\right] \theta(t)$$

By adjusting the three coefficients, the output of the controller can be made to respond to the magnitude of the error, the integral of the error and the rate of change of the error.

To consider the frequency behaviour of this system, its dynamic characteristic must first be obtained as a Laplace transform. The transformation is defined by—

$$\overline{L}\left[f(t)\right] = F(p) = \int_o^\infty f(t) e^{-pt} dt$$

It can be shown that the Laplace transform of the operator becomes—

$$G(p) = L\left[K_1 + K_2 \int dt + K_3 \frac{d}{dt}\right]$$

$$= K_1 + \frac{K_2}{p} + K_3 p$$

This expression can be regrouped into the form—

$$G(p) = K \frac{(1+pT_1)(1+pT_2)}{p}$$

In such a standard factorised form, it is possible to make a direct interpretation of its dynamic behaviour, especially as mapped in the frequency domain. For example, the amplitude sensitivity/frequency characteristic can be derived purely algebraically as—

$$A(w) = |G(jw)|$$

$$= \left| K \frac{(1+jwT_1)(1+jwT_2)}{jw} \right|$$

$$= \frac{K}{w} \sqrt{1 + w^2(T_1{}^2 + T_2{}^2) + w^4 T_1{}^2 T_2{}^2}$$

On a Bode diagram of log A against log w, such responses can be approximated to straight lines giving a response characteristic shown in Fig. 2.

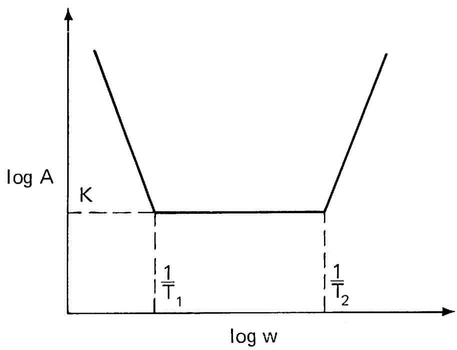

Fig. 2

The controller therefore tends to increase its sensitivity to low frequency effects such as slow drifts; it also responds strongly to rapidly changing inputs. By suitable adjustment of the original constants K_p, T_i and T_d, the distance between the corner points may be varied and the whole diagram may be moved up or down. So we see that a device that was developed with very little theoretical help can be shown to be remarkably powerful and adaptable.

Other developments

THE second world war stimulated developments in control theory for applications such as position controllers for guns. When peace came, this work was gradually published and a new generation of control engineers emerged to work in the universities and in industry. The Bell System work became the basis on which they developed the theory. The early work had been limited to linear systems with single inputs and single outputs. Although Bode gave the beginnings of an approach to the synthesis of controllers, the design criteria remained largely intuitive. Many avenues were explored and some of the more relevant ones will now be considered.

In the chemical industry, most of the processes were developed in relatively recent times and so tend to be made up of sequential operations. Each unit is designed to carry out a limited part of the entire processing. In other industries, the processes are often much older; in many cases, there are many simultaneous actions on the material. For such plants, the idealisation of single input/output loops does not really hold; instead, parts of the plant are truly multi-variable, with essential interactions between the variables.

In the post-war period, there was one attempt to tackle the problem of the control of multi-variable linear systems. The idea was to introduce a new set of inputs that would be connected to the plant via a multi-variable controller. This would be designed so as to cancel out the internal cross-coupling of the plant and leave one new input simply connected to each output.

Theoretically, this looked like a very attractive approach. In practice, there were severe difficulties. The uncoupling dynamic elements had to be obtained by an algebraic procedure that usually becomes quite unpractical for systems of order greater than 4×4. The result of the analysis may in any case not be realisable. It was also found that the non-interacting controllers often call for excessively large magnitudes of control action for quite realistic input disturbances. One final difficulty was that such systems were very sensitive to small changes in process parameters and, to make matters worse, these changes cannot be readily predicted. Thus, a promising and interesting theoretical approach has been rather limited in practical application.

Another important and still active field is adaptive control. Schemes from this source have their origin in the highly adaptive dynamic characteristics of a man performing control tasks. In adaptive controllers, the dynamic characteristics (sometimes simply the magnitude of certain parameters) are automatically adjusted. A common example would be the use of two pneumatic controllers connected in cascade. The set point of the main controller is itself changed relatively slowly in response to the performance of the system as a whole. Adaptive controllers have found application in certain single loop situations for which special purpose devices may be justified. The design task presents many difficulties: often the systems are severely non-linear, giving rise to difficult stability problems.

Non-linear dynamic systems also have received considerable attention. Much of this work is concerned with single loop problems with specific solutions to very restricted classes of non-linearity. In the process field, most problems can reasonably be linearised or may be approximated by a small number of locally linear regions. No approach has been evolved for non-linear problems that gives anything like the insight that linear systems theory offers the control designer.

Digital techniques

IN THE fifties, a number of trends favoured a new approach. The more complicated processes were being subjected to extensive theoretical and experimental study and, as a result, mathematical models of their dynamics were available to control systems designers. There was also a major development in the type of hardware that became available. Digital equipment was being developed, culminating in the most versatile of all digital devices, the real time process control computer. This type of hardware could cope with any time scale and enabled much more complex control strategies to be implemented.

The greater insight into the processes and the extra power of the control devices led to more precise design methods. For the first time, controllers could be designed to quantified system performance criteria, taking account of the actual dynamics of the plant. As digital devices operate in a discrete mode, a means of handling sampled information was required. The body of theory evolved became known as sampled data theory. The controllers that it generates are often called digital compensators. With the discrete mode of working, the earlier frequency domain proved difficult to use. A modified transform was introduced to handle these problems, which is known as the z-transform.

Many processes exhibit the property of finite time delay, that is, the output is related to the input by a fixed time delay τ—

$$\theta_o(t) = \theta_i(t-\tau)$$

Such elements typically arise when the material flows down a pipe or conveyor and emerges at the output τ time units later. In these circumstances, the three-term controller can be stabilised only if its sensitivity is greatly reduced, giving rise to sluggish control action. Digital compensators can be very effective for such situations.

The three-term controller equation is often converted into an equivalent digital form and the extra power of digital devices is used to give a wider range of time constants than can be readily realised by pneumatic equipment. This application has come to be known as DDC (direct digital control).

Although sampled data theory is a great advance, severe limitations remain. Those criteria that can be handled most readily are measures of the performance of the entire system when it is disturbed by time domain inputs such as steps. It is then possible to design controllers that guarantee a fixed percentage overshoot, a given rise time, etc. In process regulation these are not usually the most important considerations. Controllers designed for such criteria are not usually particularly successful when the system is trying to cope with the more usual random disturbances. If they are designed to compensate for one set of disturbances, they are often poor when others are applied. The technique is also limited to linear single variable systems.

In 1949, Wiener published a book that was really the conceptual forerunner of modern methods. His approach was to design controllers that minimised the future time integral of the square of the error between the input and the output. Here was a criterion much more relevant to process applications.

Although being in the time domain (the natural domain for process work as opposed to communications applications), it did not require the inputs to have any specific form. It turned out that the calculations required were formidable, largely because the analysis was performed in the frequency domain.

By the end of the fifties, computers became available that were suitable for on-line process control. In these devices, the basic arithmetic and memory of ordinary computers is supplemented by input and output channels that can pass information to and from the plant. The reliability of digital computers had improved until it was of the same order as the other instrumentation and control equipment.

The earliest applications were data logging and alarm status monitoring. A central computer was connected to a large number of points on the plant so that it could scan the general condition of the plant and report irregularities. In the first control applications, the digital form of the three-term controller equation was applied sequentially to a number of loops around the plant. The high operating speed of the computer not only made this multiplexing possible, but also offered an opportunity to make periodic assessments of the entire system performance.

The regulators ensure that the plant variables are maintained at constant values, yet one may ask what these levels should be. This is a question about the long-term performance of the plant as a whole. There are three sources of such changes—(*1*) the output requirements may change such as by a change in quality specification, (*2*) the internal characteristic may change owing to effects such as internal fouling or wear or (*3*) there may be a significant alteration in the properties of the input feed.

In such situations, the computer can periodically assess the performance of the plant and output changes in the controller set points. To do this, there must be computable performance criteria describing the relative merit of possible operating conditions. Such models will, in general, be non-linear relationships, with the added complication of constraints on the variables.

If the time scale of these changes is long compared with the time scale of the regulators, such models take the form of steady state algebraic relationships. There is a body of theory known as non-linear programming, which enables optimum sets of variables to be computed by iterative techniques. From time to time, these optimum settings may be recalculated and the appropriate action taken by the computer.

In many plants, it is possible to split the disturbance into short-term and long-term effects. Even though little insight may be needed to set the constants of the local regulators, clearly much more theoretical study is required to establish a satisfactory model of the long-term performance of the whole plant.

There have now been quite a number of such on-line optimisation schemes successfully installed, in quite a variety of process industries. Once a computer has been justified for improved or cheaper regulation, the extra cost of optimisation is mainly the cost of the initial study required to establish the model. This, in turn, is often justified by the long-term benefits derived from the better understanding of how the process actually works.

Modern state vector-matrix methods

ALTHOUGH it is sometimes convenient and feasible to distinguish between the dynamic regulation problem and the static optimisation problem, it would be a considerable step forward if the two concepts could be merged. This would enable the idea of optimisation to be applied to the whole problem, including the moment-to-moment operation of the plant. In any new approach, it would be helpful also if multi-variable problems could be dealt with and if high order and non-linear systems could be incorporated in the same framework.

Wiener had shown the way by attempting to minimise the time integral of a function of the error. Such integral criteria are particularly attractive for process engineers, as the aim of control is usually to prevent the plant operating for significant periods of time at undesirable or uneconomic levels. When attempts were made to extend Wiener's ideas to multi-variable situations, it became clear that a new mathematical viewpoint was required. This was primarily a return to time domain and a direct confrontation with the basic differential equations of the system it was also realised that there was a considerable body of mathematical knowledge about the behaviour of sets of differential equations that might be relevant to control problems.

The ready availability of powerful off-line computers enabled the resulting matrices and involved manipulations to be automated. Without this aid, any practical approach had to be easy to use, preferably graphical.

The starting point for modern methods is the set of differential and algebraic equations to define the mechanics of the system. These will be time domain equations of arbitrary order. They must first be decomposed into a set of first order state equations in canonical form—

$$\dot{x}, = f_i[x_1(t),\ldots,x\ (t),u_1(t),\ldots,u_r(t),t]$$

where $i = 1,2,\ldots,n$.

The set of variables $x_1(t),\ldots,x_n(t)$ will be the state variables of the system, if they completely determine its future behaviour given only the r inputs $u_1(t),\ldots,u_r(t)$. The state variables can be said to separate the past from the future and there must be one first order differential equation for every variable $x_1(t)$.

A vector-matrix notation may be introduced for simplicity and to clarify the structure of the equations. If the states are grouped together, they may be regarded as a vector—

$$x(t) = \{x_1(t),\ldots,x_n(t)\}$$

Similarly, the control inputs may be grouped as—

$$u(t) = \{u_1(t),\ldots,u_r(t)\}$$

If all vectors are assumed to be time-dependent, the system equations may be written as—

$$\dot{x} = f(x,u,t)$$

Much valuable insight may be obtained by considering the most general linear case. The basic interactions between the variables are preserved, yet some very remarkable results can be obtained.

The general linear form of the system equations is—

$$\dot{x}_i = a_{i1}x_1+\ldots+a_{in}x_n+b_{i1}u_1+\ldots+b_{ir}u_r$$

If all n equations are considered, they can be written in vector-matrix form as—

$$\dot{x} = Ax+Bu$$

This equation describes the interacting dynamic characteristics of the whole system. The selection of state variables is not unique and it is by no means a trivial matter to decide for complicated systems what is the minimum number of states. In the linear case, the states may be regarded as the outputs of the amplifiers of an analog computer representation of the problem. Each state represents the level of energy in a minimum energy storing element, the first order lag.

One other set of equations is required. The actual outputs that are of interest may not themselves be states of the system. Instead, they may be algebraically (as opposed to dynamically) related to the states. If they are a set $y = \{y_1,\ldots,y_m\}$, the general form of the output equation would be—

$$y = g(x,u,t)$$

or, in the linear case, the equation is—

$$y = Cx+Du$$

The state and the output equations together define the system. The general linear case may be represented on a diagram (Fig. 3), where the broad arrows indicate vectors.

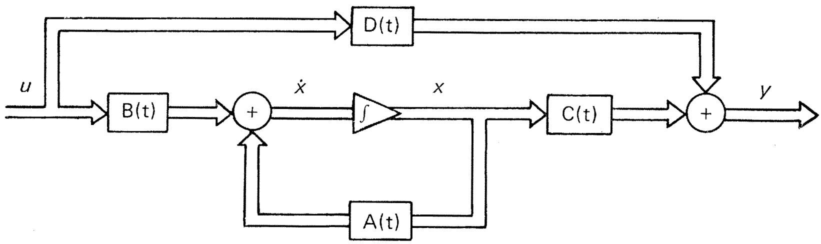

Fig. 3

The manipulation of such sets of equations requires ready access to computing facilities. The equations can also be handled if time is made discrete (as in an on-line computer application) and if some of the coefficients in the matrices A, B, C and D are not constant, but vary with time. In this way, systems that wear or decay can be handled simply within the linear framework.

Optimum control

WITH this general multi-variable time domain description of the system, the problem of controller synthesis may be approached. The aim is to generate a policy that simultaneously adjusts all the control inputs $u_1,\ldots,u_r$ so as to satisfy some optimum criterion. The type of criteria of most interest in process applications is a minimisation of a time integral. The general form would be—

$$\min_{u} \int_{o}^{T} L(x,u,t)dt$$

This implies that the cost of operating the plant depends on the future behaviour of the states, taking account of possible costs incurred by the control actions themselves. When control involves significant changes in heat input or power requirement, the total cost will need to take these actions into consideration.

A most important case of such cost functionals is the general quadratic. If the variables are scaled so as to be measured as departures from the steady state condition, a quadratic expression may be considered—

$$L(x,u,t) = x'Qx+u'Ru$$

If this is expanded, it represents the weighted sum of all terms such as $x_i x_j$ and $u_k u_l$, including the diagonal terms x_i^2 and u_k^2. If only the coefficient of x_i^2 are non-zero, then the criterion represents a minimum sum of error squares.

The designer has substantial freedom to adjust the controller's response by selecting appropriate weighting factors for the elements of Q and R. With suitable values, the system can have the property that large values of u are discouraged. This approximates to the practical situation in which the control action is bounded—for instance, a valve cannot open beyond 100 per cent.

Within this framework, a multi-variable optimum regulator may be designed. If the upper limit of the integral is set to infinity, the controller will be designed to minimise all future disturbances of the system, taking due account of the relative importance of each state and the cost of control action.

The optimum control policy can be obtained after a little analysis and is found to be—

$$u^0 = -Hx$$

where $H = R^{-1}B^1P$ and the matrix P is the solution of the matrix equation—

$$P\ BR^{-1}B'P - A'P - PA - Q = 0$$

If the elements of the matrix are constant, this policy amounts to a constant linear negative feedback structure, in which the control inputs are simple linear combinations of the states. Typically, u_k would be—

$$u = -(h_{k1}x_1 + h_{k2}x_2 + \ldots + h_{kn}x_n)$$

The principle of negative feedback has emerged from the analysis as the optimum policy for minimising integral quadratic cost criteria applied to linear dynamic systems. The elements of H can be calculated fairly simply and, perhaps more remarkable still, the structure of the optimum controller remains the same if any of the coefficients in the matrices are allowed to change with time. This control policy remains at an optimum for adaptive situations. In this case, the numerical value of H simply needs to be updated from time to time. It has been suggested that this type of controller will come to be regarded as the multi-variable equivalent of the three-term controller.

There are a number of other situations of interest to process control designers, for which optimum control theory is relevant. It is possible to design controllers that act as fast as possible by minimising time (simply put $L=1$), for example, during start-up. In another important class of problem, the plant has to undergo regular and drastic changes in operating condition. It is desirable that such transitions should be performed by simultaneous adjustment of the control variables in an efficient and systematic way. Such situations may be formulated as optimum control problems.

Any such approach must lean heavily on a basic understanding of the process. It calls also for much deeper thought about what the control objectives are and how may they be represented in a quantified criterion. Experience has shown that such techniques require a substantial amount of systems study and off-line simulation. The advent of modern high level continuous systems simulation languages such as CSMP have greatly eased the burden of this work.

Present practice and future developments

Most machines in the paper industry now have some form of automatic control. Standardisation is made difficult by wide variations that exist in the equipment configuration of individual machines. Local single loop controllers have certainly been of benefit, but many of the loops still require much manual intervention. In some areas, where very complex behaviour occurs, there is often no automatic control at all or, if it is installed, it has little effect.

On-line process control computers have definitely arrived in the paper industry. The most striking contribution they have made to improved plant performance has been the new opportunity to tie together different parts of the plant. This function of machine integration enables a dynamically co-ordinated throughput to be maintained. The computer also allows the plant to be brought into the general information management system, giving an improved allocation of work load and mill resources.

What may be expected in the near future? As the industry concentrates its production into larger and more efficient units and as digital equipment becomes relatively cheaper, many more computer installations can be expected. At the plant level, modern control theory can contribute to better control schemes for the very heavily interacting parts of the plant and to those areas where regular large-scale transitions in plant state occur.

At the mill management level, there are other new developments. Much current research activity is concerned with extending the ideas derived from the study of single plants, to the dynamic control of the whole system. It will not be long now before we have on-line schemes to relate the dynamic behaviour of individual plants to global management objectives.

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Transcription of Discussion

Discussion

Mr B. W. Balls Mr Ward has given a fine paper, but perhaps he has treated a little lightly the formative years of process control. As one long connected with 'bellows, nozzles and levers' and who has met some of the first designers, I can say that they had a deep understanding of process control requirements and the operation of their hardware. First interest was in the oil industry, where the interest was predominantly flow, as it is in the paper industry. A study of the patent literature of the twenties and thirties would demonstrate these points.

Process control began in the time domain and has returned home. I believe it was Minorsky who around 1920 published a pioneer paper on feedback based upon observations of the wake of a ship. Papers by such as Ivanoff,* Callender, Hartree & Porter† and Mason‡ analysed process lags and still make interesting reading. The Cranfield conference in 1951§ brought together for the first time process control people and the backroom boys from the services, etc. and we moved rapidly into the frequency domain. I well remember the birth pains. Much useful work was done, but frequency response analysis of real processes was a disappointment in many cases, owing to extreme attentuation and noise. There was also understandable reluctance by production managers to let their plants be waggled.

Mr Ward has stated correctly that process computers have arrived in the paper industry. It is also true that a clear definition of aims is essential. Many early installations failed because of indigestion, whereas more modest aims might have produced some success. This requires total involvement of people who are well versed in process control applications and having a deep understanding of operating skills.

The Chairman My only comment to Mr Balls is that it was the war that made radio and electronics respectable in some of the universities and many of the graduates coming out at that time were well versed in the frequency domain. It is only more recently that we have moved back into a time domain.

* Ivanoff, A., *J. Inst. Fuel.*, 1934, 7, 117
† Callender, A., Hartree, D. R. and Porter, A., *Phil. Trans. Royal Soc.*, 1936, **235** (A), 415
‡ Mason, C. E. and Philbrick, G. A., *Trans. A.S.M.E.*, 1941, **63**, 589
§ Tustin, A., *Automatic & Manual Control* (Butterworth, London, 1952)

Mr H. B. Carter Is there any significance in the continued use of a valve as an example when we talk of the single control loop? One of the earliest control systems that was applied in the papermaking process was a speed control and the earliest one of which I have any experience was patented in 1919, the Harland differential speed control.

Mr A. J. Ward As I pointed out, engine regulation was the first problem. It was really only the process industries that had an interest in the flow of material, hence the valves. If you search, you will find that there are many more valves in control situations than there are engines with speed controllers.

Dr I. B. Sanborn With regard to the modelling paper, let me say that, whenever such papers are given, I notice many people becoming discouraged by the mathematics involved. Please be assured that modelling is not as difficult as it appears. First, note that most of the processes in our industry can be modelled via a simple first order system with dead time. This means that only three parameters need to be estimated— a dead time, a gain and a time constant.

Dead time can usually be assessed by a direct inspection of the time series data available. The gain can usually best be estimated by noting the response in the output at steady state to a step of known size in the input. This can again be assessed from the time series record. This leaves only the time constant to be estimated, which is easily accomplished by any one of a number of one-dimensional search methods available.

Mr G. Donkin I agree that useful estimates of process time delays and time constants can be made without resort to prolonged mathematical analysis, especially for small systems. The techniques outlined represent some of the many tools in the model builder's tool kit. The paper was not intended as a survey of all possible modelling techniques, nor was it meant to imply that the methods outlined must be used. An appropriate mixture of engineering judgment and mathematical refinement is inherent in all modelling. The mix chosen by an engineer may well differ from that chosen by a mathematician. When the mathematicians have developed what they believe to be useful tools, it is sensible to explain them to the engineer. Engineers would welcome more 'talky-talky' explanations of recent developments such as this paper has tried to present.

The Chairman These contributions show that value is still left in simple methods than can be handled by a desk calculator.