DESIGN OF AUTOMATIC CONTROL SYSTEMS FOR THE PROCESS INDUSTRY

H. Sandvold
Norsk Hydro-Elektrisk, Kvælstofaktieselskab Oslo, Norway

INTRODUCTION

The present paper is mainly based on the experience gained from work performed by industry and research institutes in Norway over the last 5–10 years. These institutes work in close co-operation with industry under the auspices of the Royal Norwegian Council for Scientific and Industrial Research.

The Research Council was established after the last war and has initiated and co-ordinated a large selection of research activities. Research institutes have been erected to do sponsored research for industry. Projects of more general interest are financed jointly by the Council and industry. This arrangement serves to increase the research and development potential of the small industrial units which prevail in Norway. The expansion of the Council's activities is indicated by *Figure 1.*

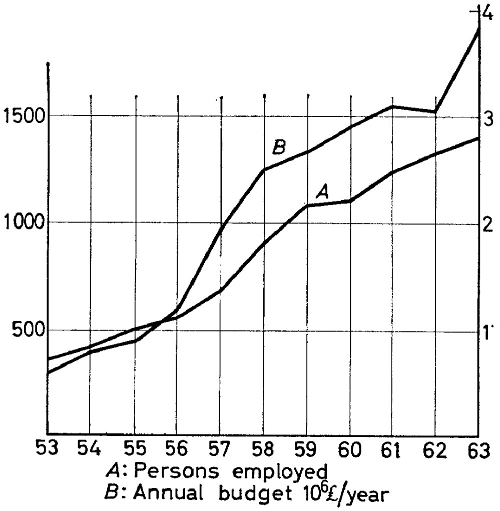

Figure 1. Activities of the Norwegian Research Council

The members of the Research Council come from Government, universities and industry. A number of technical committees work in an advisory capacity. These committees promote recommendations for new activities and submit project proposals to be acted upon by the Research Council.

They also take on the responsibility of supervising progress of work at the institutes.

The Automatic Control Committee, which has now been in existence for about 8 years, is responsible for the activities noted in *Table 1*. Industrial support to the projects is not included, nor the projects sponsored solely by industry. Roughly 50 university graduates work on control engineering projects at our research institutes.

Table 1. Automatic Control Committee activities: 1963 budget

	£
Control theory research, optimization	20,000
Process dynamics	15,000
Quality measuring techniques, instrument development	15,000
Optimization electric power systems	5,000
Machine tools numerical control	12,000
System design case study	18,000
Automation of merchant ships	14,000
Economic and social studies	6,000
Scholarships	8,000

GENERAL BACKGROUND

Process control should be considered as a part of process engineering. It is at the same time perhaps the most challenging branch of control engineering, which emerged as a new technology after the last war. Before that time process control was mostly considered as an art: how to fit instruments, regulators and valves to a process with the object of keeping selected variables within specified limits. The theory of servomechanisms, which was developed as a prerequisite for the design of military control systems, gave a sound theoretical foundation also for the design of process control systems[1].

Control engineering is a rapidly developing science. It is therefore necessary, before we start to explore the future possibilities of process control, to give a status report of what has been taken into common use by industry. It has been found convenient to split it in one section on theory and one on application.

THEORY STATUS

A block diagram for a single loop control system is shown in *Figure 2*.

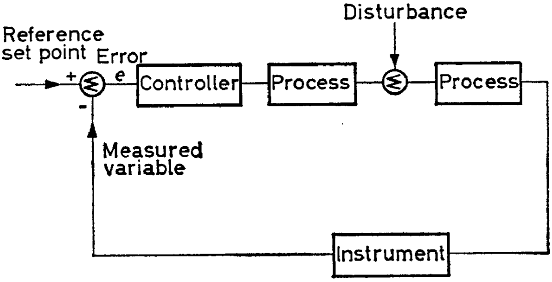

Figure 2. Block diagram; single loop control system

Linear systems are usually assumed in order to simplify the analytical treatment. The relation between an output variable $y(t)$ and input $x(t)$ in a linear network is given by a differential equation of the form:

$$y^n(t) + a_1 y^{(n-1)}(t) + \dots a_n = b_0[x^m(t) + \dots + b_m]$$

where $n \geqq m$ and all a's and b's are constant. Laplace and Fourier transforms can be used to study systems of this type. They will have rational functions as transfer function.

$$\frac{Y(s)}{X(s)} = H(s) = b_0 \frac{s^m + b_1 s^{m-1} + \dots + b^m}{s^n + a_1 s^{n-1} + \dots + a_n}$$

The frequency response is obtained if we substitute the complex s variable by $i\omega$. A pure time delay of T secs has e^{-Ts} as its transfer function and is readily studied by the L and F transforms. Time delays are frequently encountered in the chemical industry as distance–velocity lags and are not amenable to mathematical treatment by the differential equation approach.

Most standard books on control engineering list the Laplace transform of frequently encountered basic processes. Approximate methods have been developed for the rapid drawing of frequency characteristics. Stability criterions based on these diagrams permit a synthesis of controller functions when disturbances and transfer functions of Process and Instrument blocks in *Figure 2* are known. These criteria are usually based on open loop frequency characteristics of the kind shown in *Figure 3* for a two stage mixing tank system plus a time delay, controlled by proportional + integral (PI) controller. Open loop studies are easy to perform and can guarantee closed loop behaviour specified by a maximum closed loop resonance peak on a frequence diagram or transient overshoot with a step input.

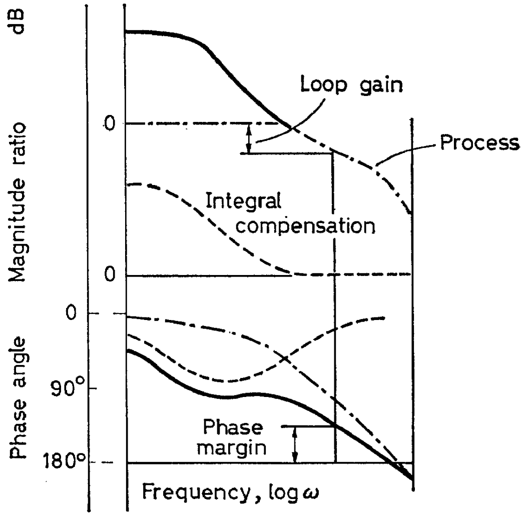

Figure 3. Open loop gain determination

Performance indices of the form

$$I_1 = \int |e(t)| \, dt$$

$$I_2 = \int e^2(t) \, dt$$

where I should be minimized, have been studied. These criteria have not gained common acceptance in process control[2].

The root locus method is an interesting extention of the frequency response method. Closed loop poles location can be studied as a function of open loop gain if zeros and poles of the open loop are known. An example is shown in *Figure 4*. Root locus has not been developed as a primary tool for control system designers.

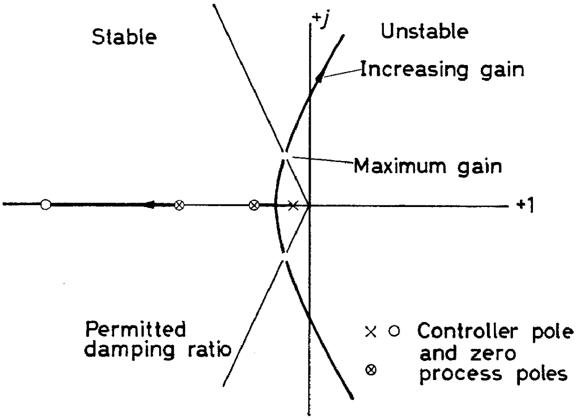

Figure 4. Root locus for 2nd order system for PI control

Many processes are controlled on the basis of samples taken at regular intervals. This is sometimes a necessity when analytical laboratory types of instruments are involved. A complete theory for sampled data systems has been developed. It opens the possibility for the synthesis of control strategy for sampled control, and gives a better understanding of the problems involved in the data processing of all measurements which are based on discrete samples. A fundamental law of sampling is that sampling frequency ω_s must be at least twice the highest signal frequency. For lower sampling frequencies signals will be distorted, as illustrated in *Figure 5*, for a signal with an upper frequency ω_c.

Non-linear phenomena exist in most processes for instance in the form of control valve characteristics or as multipliers (heat flow = temp. diff. × liquid flow).

Experience has shown that even in such cases linearization techniques give useful approximation to actual dynamic behaviour over a surprisingly large range of variables.

Special techniques which include describing functions and phase plane methods have proved useful, especially in problems of somewhat limited complexity. Describing functions are used to study frequency-independent non-linearities and give ratio of first harmonic output to sinusoidal input for varying input magnitude.

Analogue computers are used very extensively to simulate processes. This is especially advantageous in the case of large or nonlinear systems. Control systems can be synthesized on a computer on a trial and error basis.

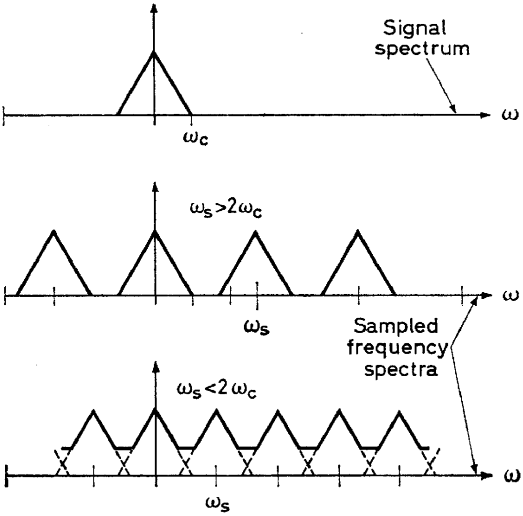

Figure 5. Influence of sampling frequency

This method has the drawback, compared to the earlier mentioned methods of mathematical synthesis, that only control functions selected sometimes at random by the designer will be investigated. A systematic approach is also needed in these cases. This point will be considered in the later section on "Theory".

It is of course necessary to know the transfer functions of processes in order to be able to apply theory for the design of control systems. Lack of this knowledge and of instruments for the determination of product properties faced the early servo enthusiasts who wanted to apply their knowledge in the process control field.

APPLICATIONS STATUS

Industry—instrument user and manufacturer in co-operation—has pushed development from the plain indicating instruments to recorders, controllers, data processing equipment and computers. Actual design of control systems will be influenced by economic considerations and process requirement, which include questions as safety considerations and product quality specifications.

Discussions on the cost of instrumentation in relation to total plant cost have been common. Reported figures vary considerably with size and type of plant as main parameters. For modern plants instrument[3] cost will be in the range 3–15 per cent. Some years ago such figures might help instrument engineers to get more instruments into plants. Such general argumentation is definitely outdated today, and it is doubtful if it ever was prevalent. Automatic control equipment should be able to give a good payoff by the following advantages: reduced capital and operating cost, including better capacity utilization, higher product quality and increased safety.

Most conventional industrial controllers can be classified in one of the following categories:

(*i*) on-off;
(*ii*) proportional plus integral plus derivative;
(*iii*) pulsed and sampled.

In the process industry most interest is concentrated on the second group. The standard P (ID) controller can be adjusted for a very wide range of gain and time constants, and it seems fair to assume that most controllers are tuned in to the process according to some standard procedure[4]. The on-off controller has a natural field of application for the control of very slow processes if changes in manipulated variables and some oscillations of the output can be tolerated.

Sampled data control is practised in most industries according to the principles in *Figure 6*. It is somewhat overlooked that this is a case of automatic control, and really represents a first step towards an automatic supervisory control system. Sampled data theory can be used to "tune" in the system, giving a minimum of laboratory expenses consistent with permitted product quality fluctuations.

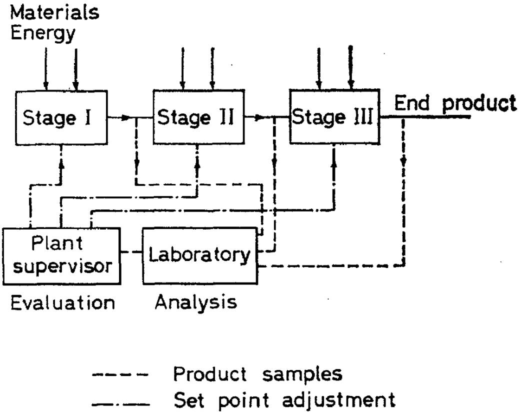

Figure 6. Sampled quality control of process

Some of the considerations which must be taken when designing control systems are illustrated by the following examples.

Figure 7 shows a polymerization reactor designed as a jacketed pan. Steam is added to raise the temperature and start off polymerization. Special care is necessary to avoid temperature overshoot in the start-up period. The controller is in this phase operated as a pure proportional controller.

Water volume has been kept low and circulation velocity high to ensure

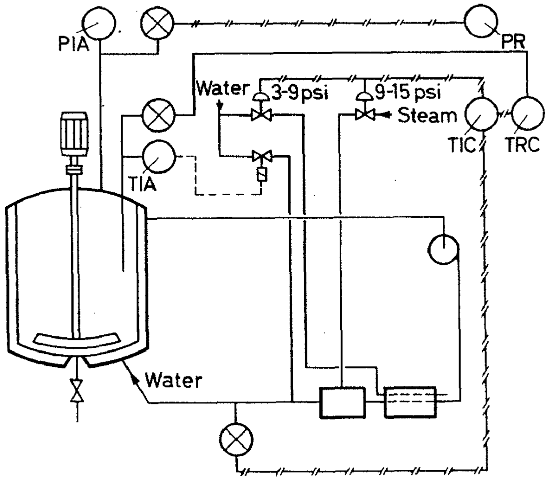

Figure 7. Polymerization reactor control

small time constants and delays and thus increasing over-all system bandwidth. For the same reason cascade control has been used. This will also serve to eliminate disturbances in cooling water supply. In case of an uncontrolled temperature rise, additional water will be added directly from the supply of cold water which is fairly abundant in Norway.

An instrumented flowsheet for an ammonium synthesis reactor with an associated steam generator is shown in *Figure 8.* Temperatures and pressures are determined by available construction materials, catalyst activity and requirement on generated steam. Standard instruments for gas analysis, temperature and pressure permit a manual optimization of N_2/H_2 ratio. Disturbances are very slow, making an automatic optimization unnecessary.

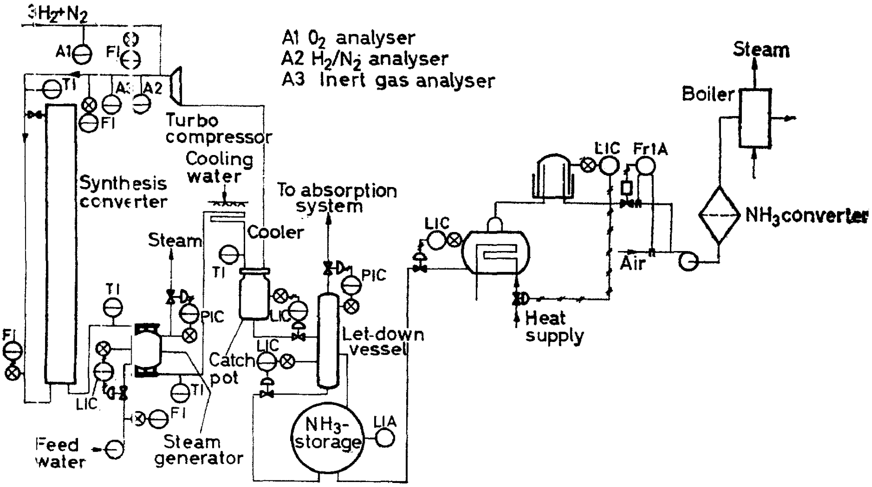

Figure 8. Ammonia plant

A very fast self-acting ratiometer has been designed to cut off NH_3 to converters when a critical NH_3/air ratio is exceeded.

Feedforward techniques are used to compensate for disturbances that appear so suddenly and are of such a magnitude that they cannot be handled by feedback controllers. This solution is of special interest for systems with time delays.

Figure 9 shows an example from a distillation column. Feed concentration is used to adjust set-point of feed flow and pressure drop across the column. Function generators can be introduced if adjustments should be non-linear functions of concentration fluctuations.

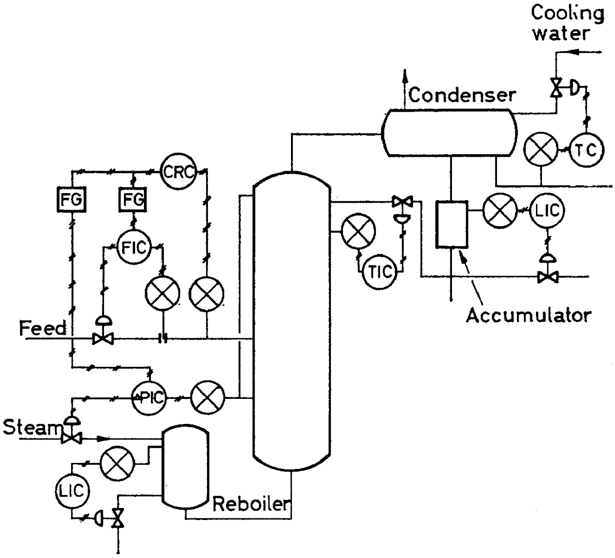

Figure 9. Feed forward in distillation column control

A typical batch process is shown in *Figure 10.* The timing central has been designed to govern 2–8 crystallizers, depending on production level, and the period of the cyclic process is continuously adjustable from 3–8 hours. The filling and emptying of crystallizers are adjusted so that adjacent process stages are not subjected to unnecessary disturbances.

We have at our disposal to-day so many possibilities to automize discontinuous processes that development work to convert batch to continuous process very rarely can be justified, with the sole purpose of getting better control of process variables.

The preceding sections have given examples of the use of some of the available tools of process control. It has been shown that control system design requires extensive knowledge about Process, Control-theory and Components. Current trends in these three sectors are treated separately in the following sections.

PROCESS

Unit process theory is the standard source of information for the design of new plants. The theory is based on fixed operating conditions and will

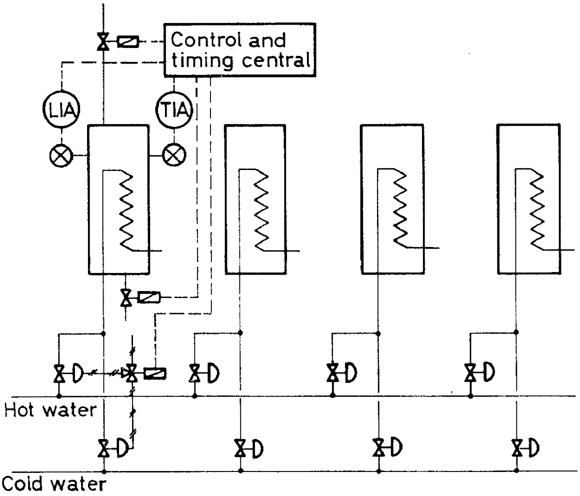

Figure 10. Control of crystallization batch process

not guide operating personnel in how to counteract the multitude of disturbances to which any real process is subjected.

Information on process dynamics was, apart from almost trivial cases, practically non-existent 10–15 years ago. The situation was somewhat the same for most instruments, controllers, and valve actuators. This situation caused the control engineers to concentrate their work rather onesidedly on the procurement of dynamic characteristics.

It seems fair to say that this early work on process dynamics was initiated by control engineers who wanted a quantitative background for the design of control systems. Much work was done on rather randomly selected equipment. It was a contribution in itself to carry through the experimental investigations. Special high speed instruments had to be developed along with signal generators.

Final results were presented in the form of frequency diagrams. It was mostly a question of a black box approach, where little attention was paid to the correlation of mathematical parameters and physical and chemical constants.

Process dynamic investigations aim at giving a mathematical model of the process, which is able to satisfy the need for more extensive process information. The rapid development of digital and analogue computers after 1950 has made very complicated process models amenable to mathematical analysis. Process dynamics has therefore become a tool in process development from bench scale to plant design[5–7].

Process dynamics investigations have been conducted in the four main process groups:

(*i*) Fluids in motion; representative examples: flow of compressible and incompressible fluids in tanks, compressors, valves and pipelines. Mixing and pulsations have been studied.

(*ii*) Thermal processes include the study of basic thermal processes as convection and radiation applied on a large selection of industrial heat exchangers.

(*iii*) Mass transfer includes important processes as absorption, crystallization, extraction, distillation, and drying.

(*iv*) Chemical processes cover a large selection of different reactions taking place in a wide variety of reactors. Process conditions are influenced by fluid flow, heat, and mass transfer.

The form of mathematical model will depend upon the purpose for which it is intended. The study of process mechanisms usually requires more detailed models than control system design. Much work remains to be done before precise requirements to mathematical models can be formulated. Accordingly, the present tendency may be to overcomplicate.

Our own work on process dynamics started in 1953. Before that time the author had been engaged in the investigation of distillation column characteristics at M.I.T. These investigations had proved to be more difficult than was anticipated at the start. On this background we decided to pick as the first process in our programme an assembly of pressure vessels[8]. The system was simple enough to allow us to concentrate on measuring techniques and gradually increase the complexity by the introduction of additional pressure vessels and interconnecting pipelines and valves. Measured frequency and transient response gave very good agreement with the developed theory based on relevant physical quantities which covered isothermal, polytropic and adiabatic processes.

Further investigations include a simple boiler, shell-tube type steam/water heat exchanger[9], rotary dryers, liquid mixing tanks, single- and multi-stage evaporators[10]. The net result of this work has been that for a large selection of process equipment we feel quite confident of our ability to construct mathematical models which can be used to study design of control systems and plant equipment.

Development is proceeding so rapidly in this field that much information is still of a proprietory nature. There can, however, be no doubt that process research centres and big petroleum and chemical companies make extensive use of mathematical models and advanced computing techniques in their design work.

Most process engineers seem to like the direct contact they get with a problem when using an analogue computer. This advantage gets, however, somewhat lost on the study of larger systems. Even a single stage evaporator, as shown in *Figure 11*, has the fairly complicated block diagram in *Figure 12*, where only dynamic functions have been written down. This diagram was used to design on an analogue computer the control system for a 3-stage evaporator process. Pressure and liquid level was controlled on all stages, concentration only at exit stage 1. *Figure 13* shows simulated curves for response of concentration x and flow q caused by a 5 per cent change in feed concentration.

Figures 14–16 come from the simulation of a heavy water production process. The process is built around a multi-stage electrolysis plant where an increase in concentration of D in H is obtained. The H_2 gas is

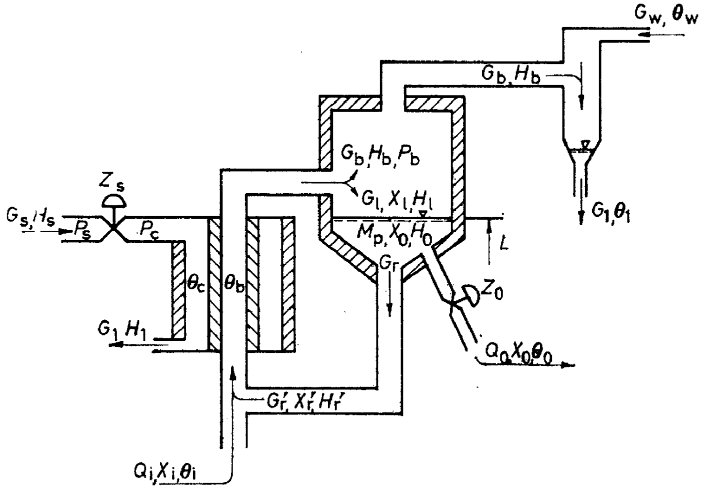

Figure 11. Single stage evaporator

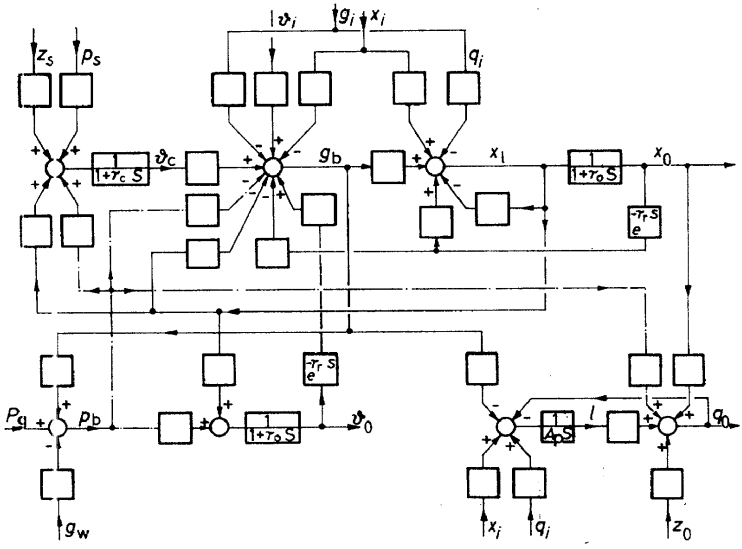

Figure 12. Block diagram of evaporator

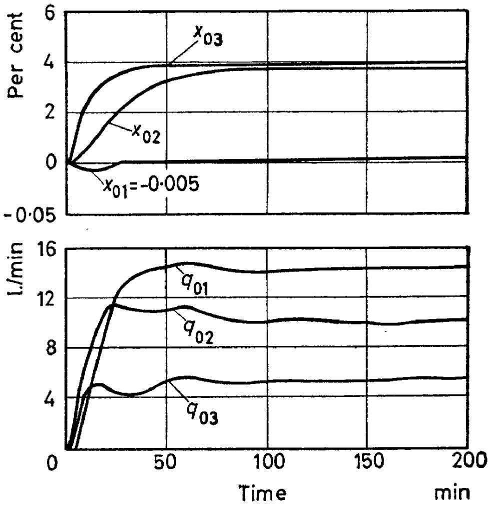

Figure 13. Three-stage evaporator transient response

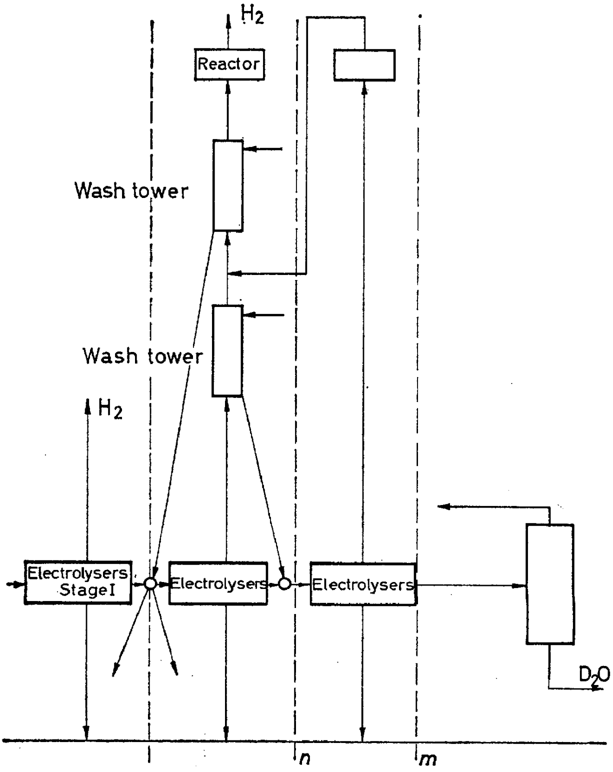

Figure 14. Heavy water plant process diagram (compressed in 1 stage)

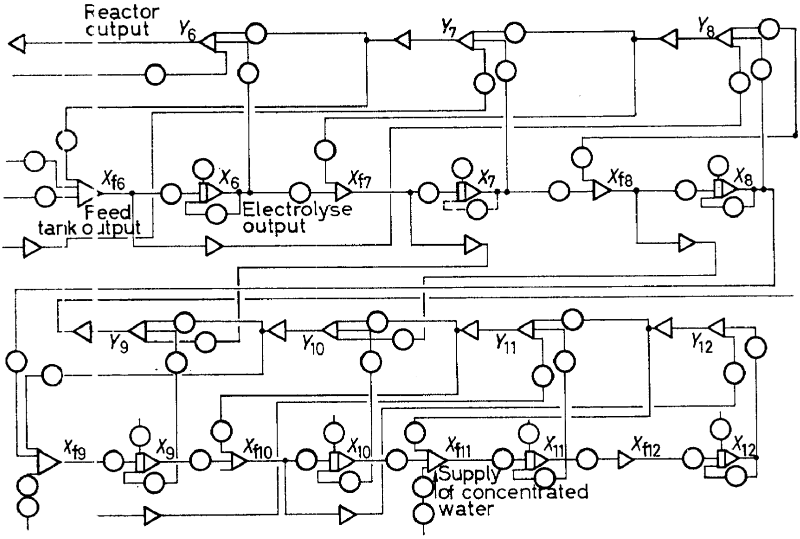

Figure 15. Heavy water simulation ($\frac{1}{2}$ of actual diagram)

in addition for each stage passed through catalytic exchange reactors where D_2 is stripped from H_2.

The electrolytic separation effect is caused by the larger over-voltage of D^+ as compared with H^+. In the heterogeneous reactors the equilibrium between D_2 and H_2O at operating temperatures results in an enrichment of D in the water vapour.

Each stage on the flowsheet shows the electrolysers, two wash towers where the gas is saturated with condensate of the right concentration, and one reactor for the heterogeneous catalysis. The final concentration from 10 per cent is made by distillation.

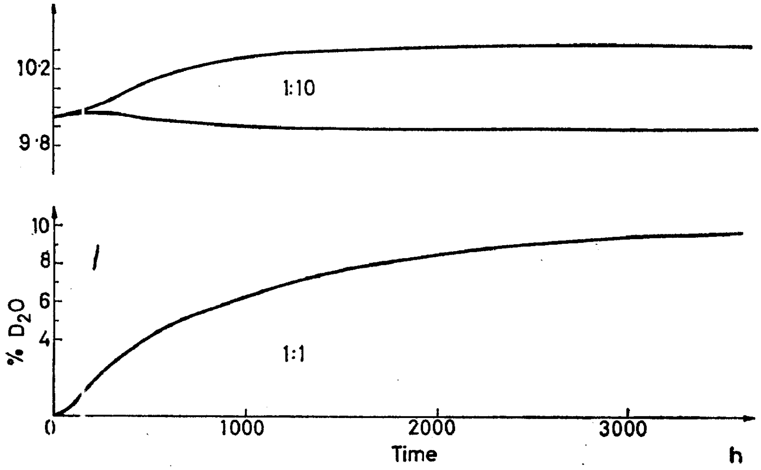

Figure 16. Heavy water concentration changes

The influence of the following process variables was studied:

Mol. ratio H_2/H_2O in the reactors
Sprinkling water to the washtowers
Catalyst activity
Electrolytic separation factor.

The investigation solved the following problems:

Optimal size of reactors and
Optimal size of other important process equipment
Optimal layout for a given electrolytic plant capacity.

Because of the extremely large time constants involved, experiments are very difficult to perform on the process, and data from the simulation studies proved very valuable to help plant operators to get a tighter control of the plant.

There is a close connection between the study of dynamic properties of processes and reaction kinetics[11]. As an example, let us consider a chain of n reactors, each with a volume V/n. Perfect mixing is assumed, reaction type A → B with velocity constant k. Process diagram is shown in *Figure 17.*

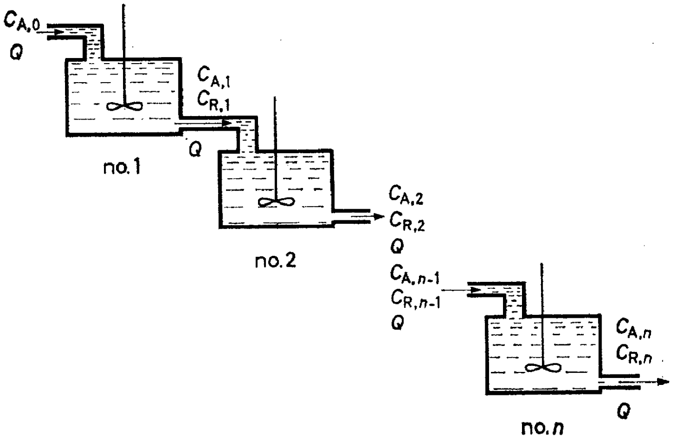

Figure 17. Cascaded chemical reactors

Convertion efficiency is shown in *Figure 18.* Based on isothermal conditions the following transfer function can be developed:

$$H_n(s) = \frac{C_{R,\,n}}{C_{A,\,0}} = \left[\frac{1}{1 + \frac{\tau}{n}s}\right]^n - \left[\frac{1}{\left(1 + k\frac{\tau}{n}\right)\left(1 + \frac{\tau}{n+k}\,s\right)}\right]^n$$

Example:

$\eta = 0{\cdot}9$ From *Figure 18*
$n = 1$ $k\tau = 9$ Relative volume $= 1$
$n = 2$ $k\tau = 4{\cdot}3$,, ,, $= 0{\cdot}48$
$n = 4$ $k\tau = 3{\cdot}1$,, ,, $= 0{\cdot}34$
$n = \infty$ $k\tau = 2{\cdot}3$,, ,, $= 0{\cdot}26$

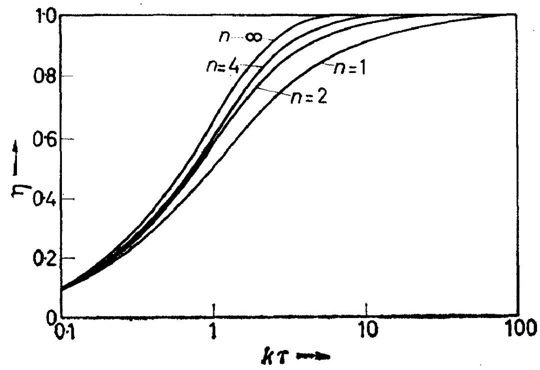

Figure 18. Conversion efficiency

Corresponding amplitude and phase diagrams are shown in *Figure 19*, which will give a foundation for the synthesis of a control system.

Another example is represented by the investigation of a batch process with fixed cyclus time[12]. Reaction is:

$$A \xrightarrow[k_1]{} R \xrightarrow[k_2]{} S$$

R is final product and S represents an unwanted side reaction. The velocity

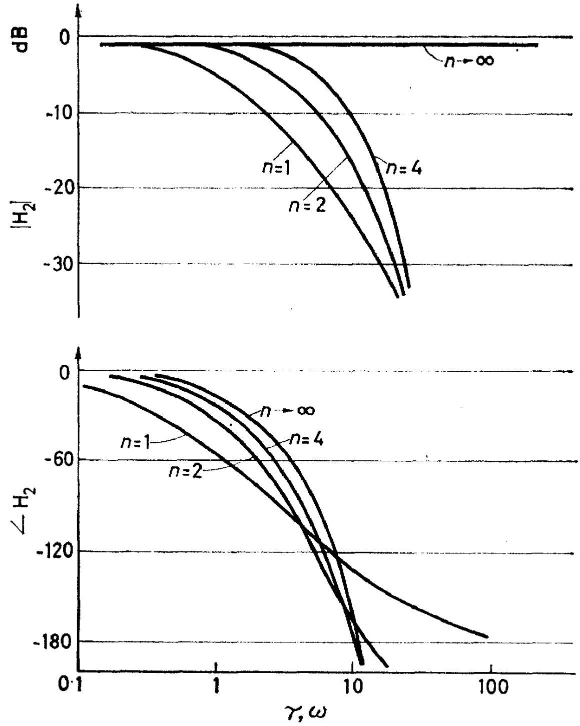

Figure 19. Frequency response of chemical reactors

constants vary with temperature according to the Arrhenius equation. Our optimizing problem is to maximize C_R, and we assume a temperature control system which will give us prescribed reactor temperature if we adjust set-points. The problem can be solved by variational calculus or by trial and error procedures where a repetitive analogue computer can be used.

Figure 20 shows some computed results. Due to disturbances, curve *C* has

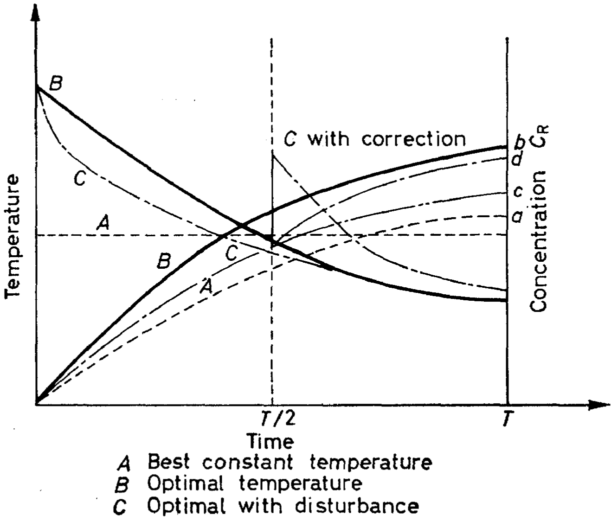

Figure 20. Batch process optimization

a departure from optimal behaviour. An adjustment is made at *T*/2 but some loss of production is unavoidable. Control of the process can be realized according to a fixed programme if disturbances are small. An analogue computer can, if necessary, be used for the on-line control of the process, *Figure 21.*

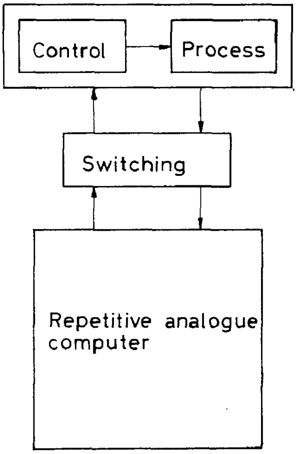

Figure 21. Batch reactor control

Dynamic investigations have in some cases been used with success to explore process mechanisms. In one investigation hydraulic flow patterns and mass transfer in falling films were studied on the basis of cyclic changes in film liquid electrolytic conductivity[13]. The experimental set-up is shown in *Figure 22.* Frequency response was measured over a large frequency range for Reynolds numbers from 50–1000. *Figure 23* shows results for $R_e = 855$.

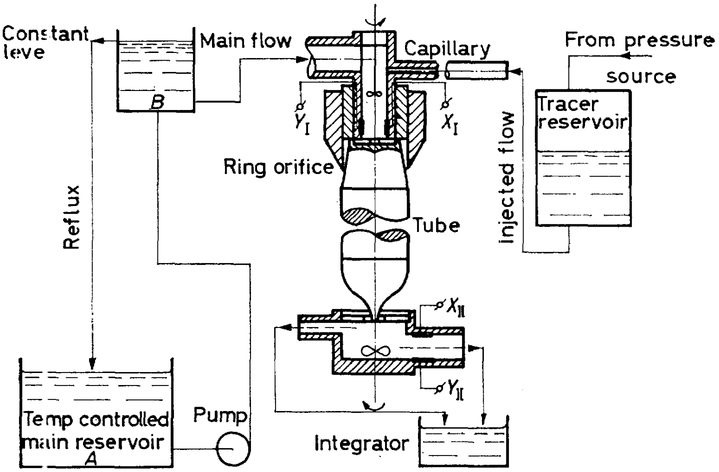

Figure 22. Falling film investigation

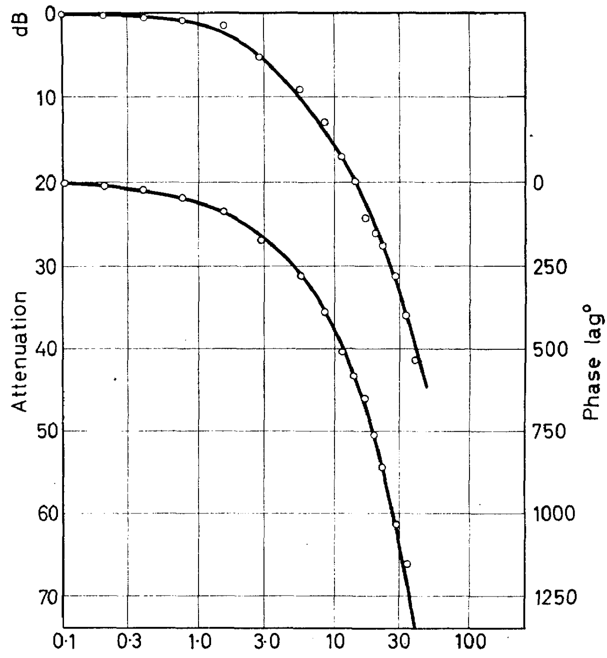

Figure 23. Falling film frequency response

Practical methods for the determination of dynamic characteristics are all based on the study of process response to a known input signal. They differ by the type of signal used, experimental equipment and the data processing of measured results. Input signals can be divided into three categories:

(*i*) Transient signals—step and pulse functions.
(*ii*) Periodic signals—sinus, multi-frequency signals.
(*iii*) Randomly varying signals—generated or existing stochastic signals.

The accuracy of measured result will be influenced by several factors to be determined by the investigator.

Signal type and amplitude
Time for measurements
Bandwidth of instruments
Sampling frequency
Data handling method.

Most methods assume linear systems. Noise and non-linearities will introduce errors. A rather thorough investigation of the importance of these factors has been carried out[14]. This paper will therefore sum up some important points only.

The most frequently applied transient signal is the step function. It has most of its power concentrated at low frequencies and should therefore be used for the investigation of rather uncomplicated processes where one-time constant and one-time delay may be dominant factors. The method gives an easily accessible indication of process dynamic behaviour, for instance by the simple manipulation of a valve.

A modified technique for pulse testing has been used quite extensively[15]. The method seems best suited for systems with a low noise contents and where a rather large input pulse can be tolerated.

The pure frequency analysis concentrates all power on one frequency at the time, which makes it easy to get an acceptable signal/noise ratio. In the case of white noise, error will be inversely proportional to the signal amplitude and to square root of recording time for each frequency. If we assume a stationary system, the error can always be reduced to an acceptable limit. The method is very time-consuming with the long time constants that may occur in the process industry. We have found a motor driven signal generator convenient for frequency tests. The input sinewave is generated by a brush-commutator system built on printed circuit cards[16]. Multiplication and integration, which is necessary for the decomposition of the output signal in an inphase and quadrature component, is carried out continuously. The same type of card is used for generator and multiplier. *Figures 24* and *25* should be self-explanatory.

In much of our work we have to some extent standardized on a modified method for frequency analyses originally suggested by Professor Jensen, Copenhagen[17]. The input signal in the so-called multi-frequency method

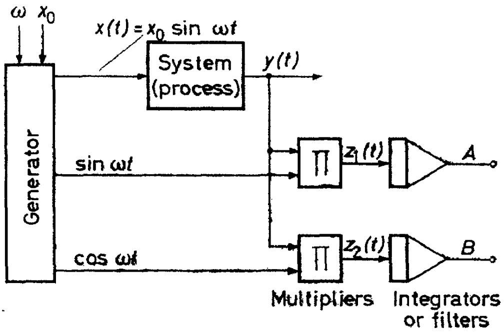

Figure 24. General process analyser

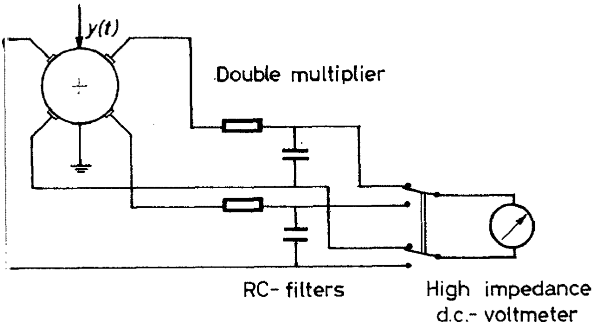

Figure 25. Multiplier–integrator circuit

consists mainly of 7 frequencies with equal amplitude and spaced 1 octave apart according to the formula:

$$f(t) = \cos \omega t - \cos 2\omega t + \cos 4\omega t - \cos 8\omega t + \cos 16\omega t - \cos 32\omega t + \cos 64\omega t.$$

This signal can be closely approximated with a square wave as shown in *Figure 26.* The signal is readily generated by a switching arrangement which can be connected directly to a rotating signal generator. Records are evaluated by Fourier analysis, and we have found it practical to use a standard digital computer programme for this purpose.

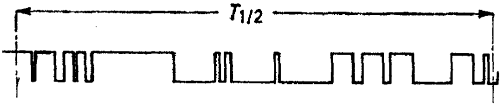

Figure 26. Multi-frequency signal

A typical recording from an investigation of an evaporator is shown on *Figure 27.*

The use of statistical methods in various forms has attracted the attention of most research-minded control engineers. This method opens up the possibility of determining process characteristics from existing noise on measured variables. The noise must have such a power spectrum that the interesting frequency range is covered. If input to process is $x(t)$, output $y(t)$ the auto- and cross-correlation functions are $\phi_{xx}(\tau)$ and $\phi_{xy}(\tau)$. Recording should be approx. 10 Tm where Tm is the maximum value of τ for which the correlation functions are considered. The correlation functions can be modified by standard "window" techniques before they are Laplace-transformed to get power spectra Φ and transfer function

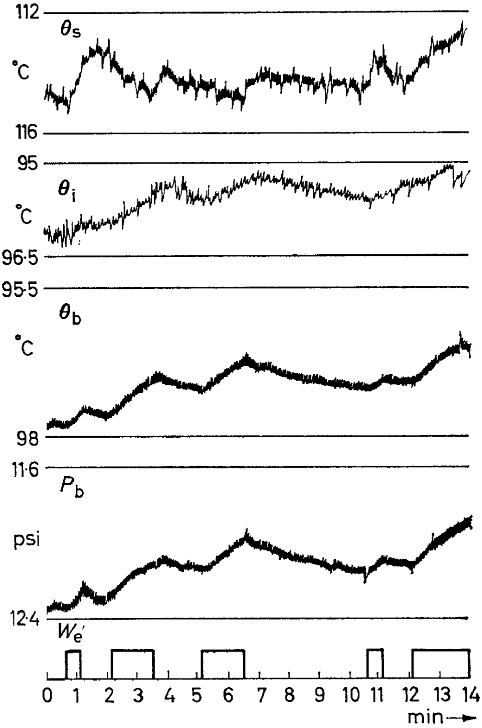

Figure 27. Multi-frequency signals from evaporator investigation

$$H(s) = \frac{\phi_{xy}(s)}{\phi_{xx}(s)}$$

This method can be used for the computation of transfer function also with a deterministic input signal. If the input signal consists of discrete and known frequencies, conventional Fourier analysis should be used.

We found the possibilities to use statistical techniques for plant investigations so promising that we built a special purpose analogue computer for this work. ISAC has two multitrack magnetic tape recording heads, and tape speed can be varied over a range of 1024:1. Movement of recording heads makes it possible to get the time shift necessary to compute correlation functions.

We used the computer to some extent to compute transfer functions but found it more useful as a tool to characterize signals in processes. It has also been used to explore process mechanisms. As an example can be mentioned an investigation of pressure and temperature fluctuations in a heavy water boiling reactor and of mixing tanks based on the measurement of electrolytic conductivity in the outlet stream.

The use of adjustable dynamic models to determine process characteristics represented a further development[18].

The general principle is illustrated in *Figure 28.* A test signal $x(t)$ is applied over some finite time T. The system output contains additive noise $n(t)$ so that only $z(t) = y(t) + n(t)$ is measureable. Now a model h of the system is simulated and the input $x(t)$ is applied to the system and the model in parallel. The model usually has a fixed structure but with several adjustable parameters. The model output is then compared to the noisy output $z(t)$ according to some error criterion, and the model parameters are adjusted until the error becomes a minimum, following some preselected strategy. The resulting model configuration is said to be the "optimum" approximation to the system. As error criterion has been used

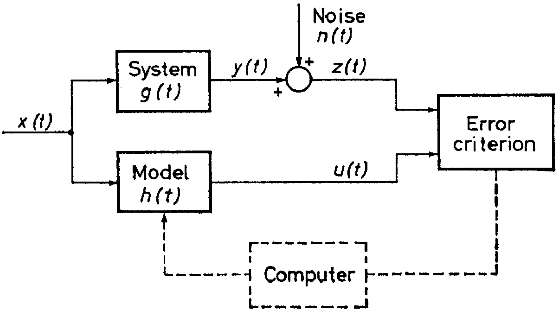

Figure 28. The use of dynamic models

$$\epsilon = \int e^2\,(t)\;\mathrm{d}t = \text{min.}$$

A cyclic adjustment of parameters one at a time has been used until local minima occur. Using ISAC, the error measure is plotted on an xy recorder. The parameter adjustments are then based quite simply on the plotted ϵ-points.

When ϵ is a quadratic form it may in 2 dimensions be represented by a family of ellipses ϵ = const. The approach to optimum will then, with cyclical parameter adjustments, look as in *Figure 29.* The adjustment of one parameter will proceed until the trajectory becomes tangent to the family of ellipses. The loci of such points will be two diameters in the ellipsis as indicated in the figure. The speed of convergence clearly depends on the angle ϕ between the diameters. In case a the convergence is good, in b poor. This has been mentioned in some detail because of the similarity of this problem to that of process optimization by evolutionary operation or hill-climbing technique.

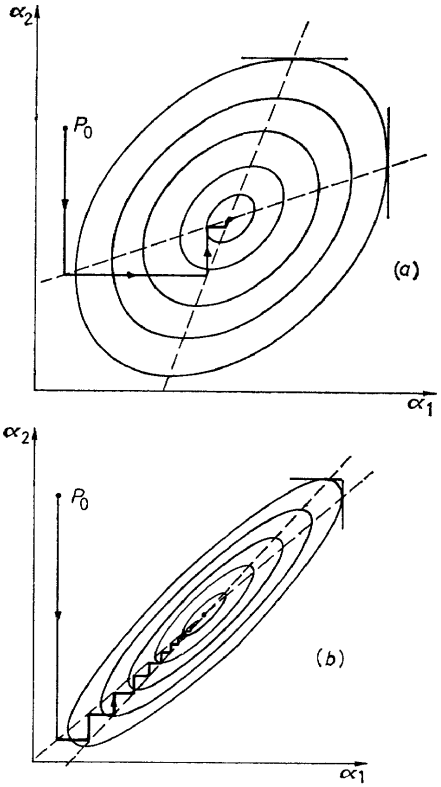

Figure 29. Stepwise adjustment of model

The use of ISAC in model experiments is illustrated in *Figure 30.* The input $x(t)$ and the output $y(t)$ of the system to be studied are recorded on a tape loop and then played back continuously during the adjustment procedure. The playback signal x, corresponding to the system input, is applied

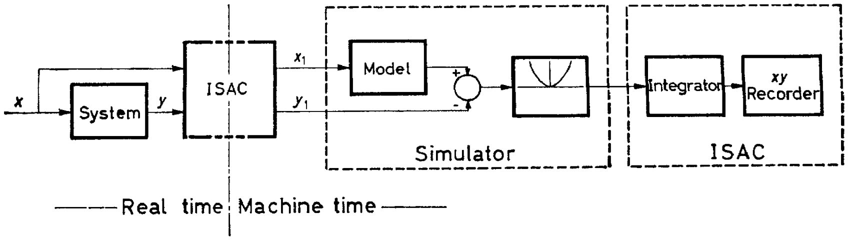

Figure 30. ISAC used in model experiment

to the model, simulated on an analogue computer. The other playback signal y, is subtracted from the output to yield $e(t)$ which is then squared and integrated. By using the integrator in ISAC, one can automatically plot the resulting value of ϵ, one point per revolution of the loop. Operation and resetting of the model is controlled by triggering circuits in ISAC, so that initial conditions are maintained in all runs.

The time-scaling problem is easily solved when the test signals are recorded at a sufficiently low tape speed. The inclusion of a pure time delay in a model is usually a difficult problem. In ISAC this may be easily achieved if one simply displaces one head during playback giving a maximum delay of approximately 5 minutes in real time.

An example is furnished by an investigation of a system which in real time had the following transfer function:

$$G_1(s) = \frac{a_0}{b_0 + b_1 s} e^{-ts} = \frac{1}{1 + s} e^{-6,\ 11s}$$

The corresponding model transfer function is

$$H_1(\Delta) = \frac{\alpha_0}{\beta_0 + \beta_1 s} e^{-\tau s}$$

Recording of the three signals x_1, $4y_1$, $4z$ are shown in *Figure 31.*

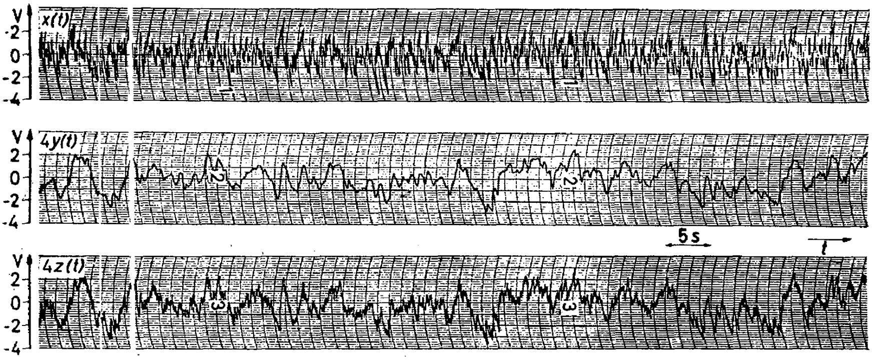

Figure 31. Recorded signals

If we start the adjustment procedure arbitrarily at

$$x_0 = 0{\cdot}6 \quad \beta_1 = 0{\cdot}714 \quad \tau = 20 \text{ mm displacement}$$

10 parameter adjustments lead to the optimum values.

$$x_0 = 0{\cdot}96 \quad \beta_1 = 0{\cdot}99 \quad \tau = 30 \text{ mm } (6{\cdot}1\ s)$$

The 4 per cent deviation of x_0 might be caused by a systematic error.

Systems of higher order and also systems with nonlinearities have been tested by the same method. In the important case of 2 time constants plus a time delay, containing 4 parameters, accuracies of better than 5 per cent have been demonstrated. Work will continue to improve the method still further and we expect to develop it into a powerful tool for the further exploration of the utilization of mathematical models in process engineering.

For some of the usual test procedures the influence of frequency independent non-linearities of the type shown in *Figure 32* has been investigated[14]. The curves are all of the form:

$$z = A_1y + A_2y^2 + A_3y^3$$

The investigations were performed with dynamic blocks of 1st and 2nd order in cascade with the static non-linearity. With a 10 per cent non-linearity the results were for the following input signals:

Sinus: No phase error; less than 5 per cent amplitude error.

Square wave: No phase or amplitude error for symmetrical non-linearity; in the other cases 5–10 per cent phase error and 5–20 per cent amplitude error.

Multi-frequency (Jensen): Phase error 1–2 per cent; amplitude error 2–5 per cent; maximum 10 per cent at high frequency and two-sided saturation.

Pulse train: Phase error 5–10 per cent; amplitude error 5–15 per cent.

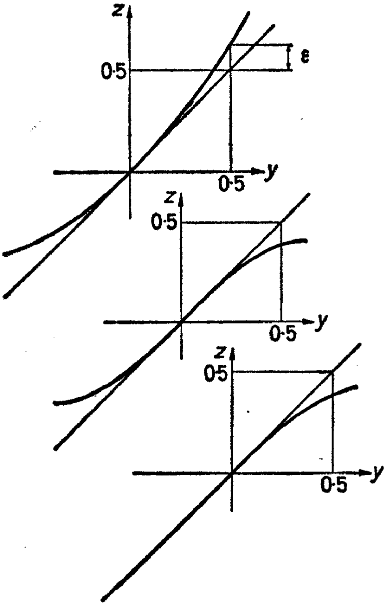

Figure 32. Typical non-linearities

As a conclusion sinus or multi-frequency signals should be preferred if there is reason to believe that the process has non-linear elements of the type shown in *Figure 33*.

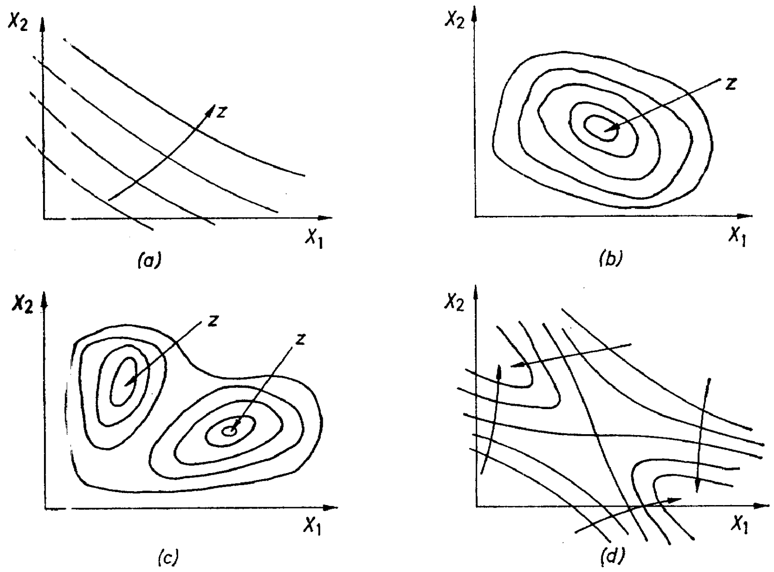

Figure 33. Static performance curves

CONTROL THEORY

Control engineering research is to-day mainly concerned with non-linear theory, multi-loop systems, adaptive control systems, optimizing control. It is not possible in this survey to cover all these fields. They all represent broad and challenging research areas, where much work is still to be done before integrated systems for optimal supervisory control can be designed as part of normal process engineering activity.

Most control engineering research as such in Norway is concentrated on the question of dynamic optimization. Many processes have what can be loosely defined as a best operating point. If the process is not subject to disturbances, the situation may be as shown in *Figure 33* when two variables influence optimal conditions. For the further discussion process variables are split up in 3 classes[19]:

(*i*) output variables y;
(*ii*) manipulated variables x;
(*iii*) disturbances u.

All three variables usually influence the performance criterion of the process. In practical cases reliable and representative measurements of relevant variables will not always be available, and extensive process investigations may be necessary before a performance criterion can be formulated. We assume a linear process, and in vector notation the interdependence of variables may be written:

$$y = \mathbf{G}(s)x + \mathbf{D}(s)u$$

when **G** and **D** are matrices. The control problem is to maximize or minimize a performance measure defined by:

$$I = \int_0^T q(x, y, u)\mathrm{d}t$$

Our investigations have been concentrated on the cases where q is a quadratic function of x, y and u.

Under static or slowly varying conditions optimum control can be reached by some sort of hill-climbing techniques, which, as with all forms of control, can be executed either as a manual or an automatic procedure. In many cases when the process is subject to disturbances, which can be external or internal, one will find that hill-climbing techniques are so slow that the process on the average will stay away from its optimal point. A theory has been developed, which makes use of known process characteristics to give all degrees of optimization from the pure static to the perfect dynamic, the latter requiring a full knowledge of the future behaviour of all disturbing signals. The complete mathematical derivation is rather involved and a simple example is selected to show some of the consequences. The block-diagram of the process is shown in *Figure 34*. In case II there are longer time constants between x_1 and y_2 than in case I.

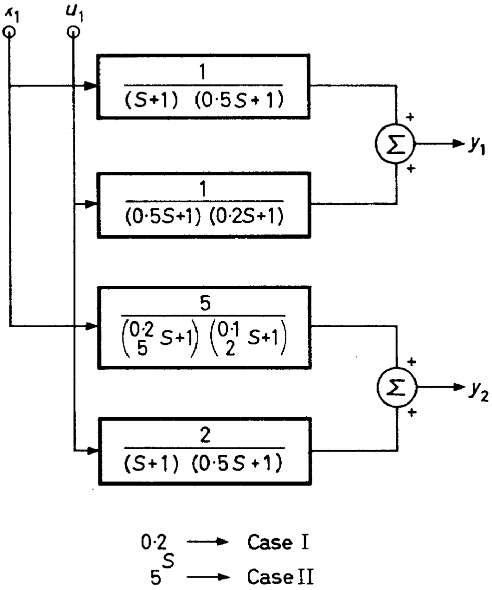

Figure 34. Process to be optimized

A performance criterion is selected according to the following equation:

$$q = x_1^2 + y_1^2 + y_2^2$$

Figure 35 shows how the performance varies when the process is subject to a step disturbance. *Figure 36* indicates the meaning of the different types of optimization.

Theoretical work on adaptive systems, optimization and multi-variable systems, has advanced a long way, and there seems to be an ever-widening gap between advanced theory and industrial application. This statement is valid in spite of the fact that computers have already been taken into use for the control of complex processes. In most cases the computer solution is only a natural extension of existing control structures, characterized by the influence of one output on one input variable.

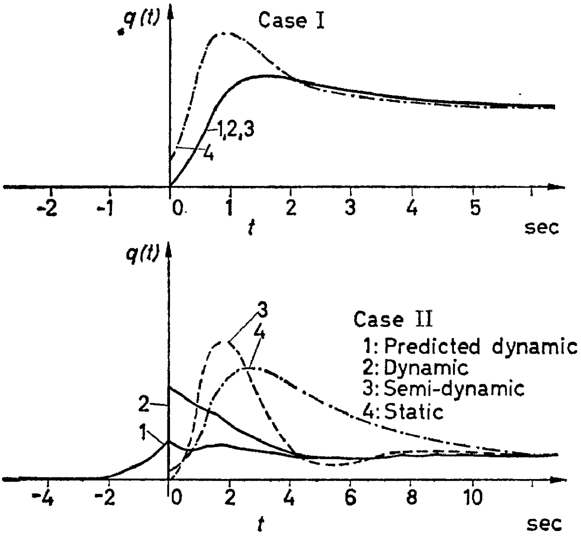

Figure 35. Transient change of performance

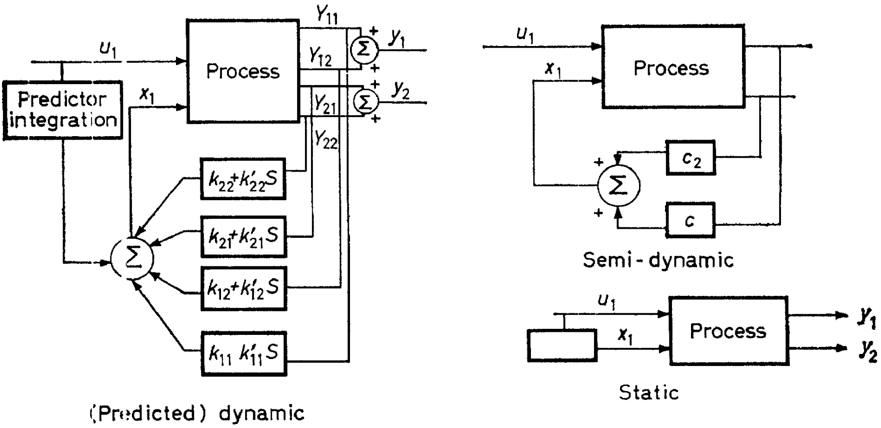

Figure 36. Different types of optimization

To be able to decide if advanced control engineering theory is likely to be of any real industrial significance, I believe it is now necessary to try out some of the consequences on rather simplified processes. In this way one may get some feeling of the engineering problems involved in the design of complex systems and the accruing advantages in operation. As this experience is being built up, the complication of systems under investigation can gradually be increased. For this special purpose the Research Council has procured a medium-sized digital GIER computer[20] to work in conjunction with an analogue machine. The system has recently been installed. Programmes for the initial investigations have been written and we expect to get the first technical reports in the near future.

COMPONENTS

A large selection of electric, pneumatic and hydraulic components is available for the solution of automatic control problems posed by industry. From a purely technical point of view the lack of suitable control components and of instruments for the most common variables as temperature, flow and pressure is no obstacle to further automation in the process industry. It is, however, not always easy to find an acceptable compromise between what is technically feasible and economically acceptable. In my own evaluation I do not think it is fair to assume that we can expect important price-cuts per component or mathematical function. It must, therefore, be left as a challenge to process engineering to design complete operating systems that are optimal from a capital point of view also. A few general remarks on the main types of industrial instruments may be appropriate.

Pneumatic instruments are most widely used. Over the years these instruments have developed into a system of standardized building blocks allowing the customers to put together components from different manufacturers. The pressure range 3–15 psi is standard also in Eastern Europe. Most instrument manufacturers market a large selection of pneumatic computing elements to perform important mathematical operations[21], a selection of which is listed in *Table 2*. In many cases we are still far from being able to utilize the possibilities offered by such rather simple

Table 2. Standard computing functions for pneumatic and electronic instruments

Function	*Input*	*Output*
Add	$A_1 \ldots . A_n$	$\Sigma K_i A_i + A_0$
Subtract		
Multiply	A, B	$(K_1 A + K_2)(K_3 B + K_4)$
Divide	A, B	$(K_1 A + K_2)/(K_3 B + K_4)$
Root extraction	A	$\sqrt{(K_1 A + K_2)}$
Integration	X	$\dfrac{X}{Ts}$
Time lag	X	$\dfrac{X}{Ts + 1}$

devices, and it is on this background that one might feel quite reluctant to raise the question of computer control at all.

Electric and electronic instruments have been in wide use for a long time in industry. The development of electronic transmitters and controllers has been very rapid over the last ten years, primarily as a result of the availability of solid state components. Several manufacturers offer complete lines of electronic instruments built up according to the same functional principle as pneumatic instruments. Signal ranges have as yet not been standardized. There is, however, a tendency to use d.c. transmitted signals. European continental manufacturers prefer a dead zero and Anglo-American manufacturers a live zero. Electronic instruments give more readily an opportunity to tie in data logging equipment. The selection of computing elements is also greater. The most important difference between the two systems may be their different abilities to transmit signals over large distances. It is sometimes indicated that pneumatic instruments should not be used over distances greater than approximately 600 ft. If local control loops are used, pneumatic instruments can, however, be used over considerably longer distances.

A German investigation has compared some makes of electronic and pneumatic instruments[22]. Lack of hysteresis in electronic instruments may in critical cases result in slightly improved control. The potential high speed of the electronic system cannot be utilized until the conventional pneumatic, electro-pneumatic or electro-hydraulic valve actuator get 5–10 times faster. The pneumatic valve actuator is the most widely used also with electronic controllers. Requirements to explosion proof equipment vary in the different countries. This may hold back the rapid introduction of electronic instruments[23].

Both pneumatic and electronic instruments satisfy industrial requirement very well. It seems fair to assume that they will be used side by side for many years.

In many plants there is an extensive need for interlocks, alarms, sinals and timers. Such equipment may be required for safety reasons, or as part of an automatic control system for batch processes. Nor should it be forgotten that in many process industries, for instance fertilizer manufacturing, solid materials handling is an important part of the over-all activity. Modern transport systems and machines for various forms of automatic packing make extensive use of what can be classified as mechanization. Limit switches, timers, electric relays have for a long time been used in industry to solve important problems in this area.

A new set of components, generally classified as logical elements, have been developed over the last few years. Solid state components are used to perform switching functions. Standard units are "*and*" "*or*" "*inverters*", *registers* and *memory* elements. The same functional elements are used in digital computers, but industrial units work at a much lower frequency, approximately 10 Kc/s. Logical elements can be used instead of relays, especially in complicated systems and where switching rate is high. They can also be used for the design of digital instruments and control circuits.

Some of the basic possibilities are shown in *Figure 37*[26]. Our own experience

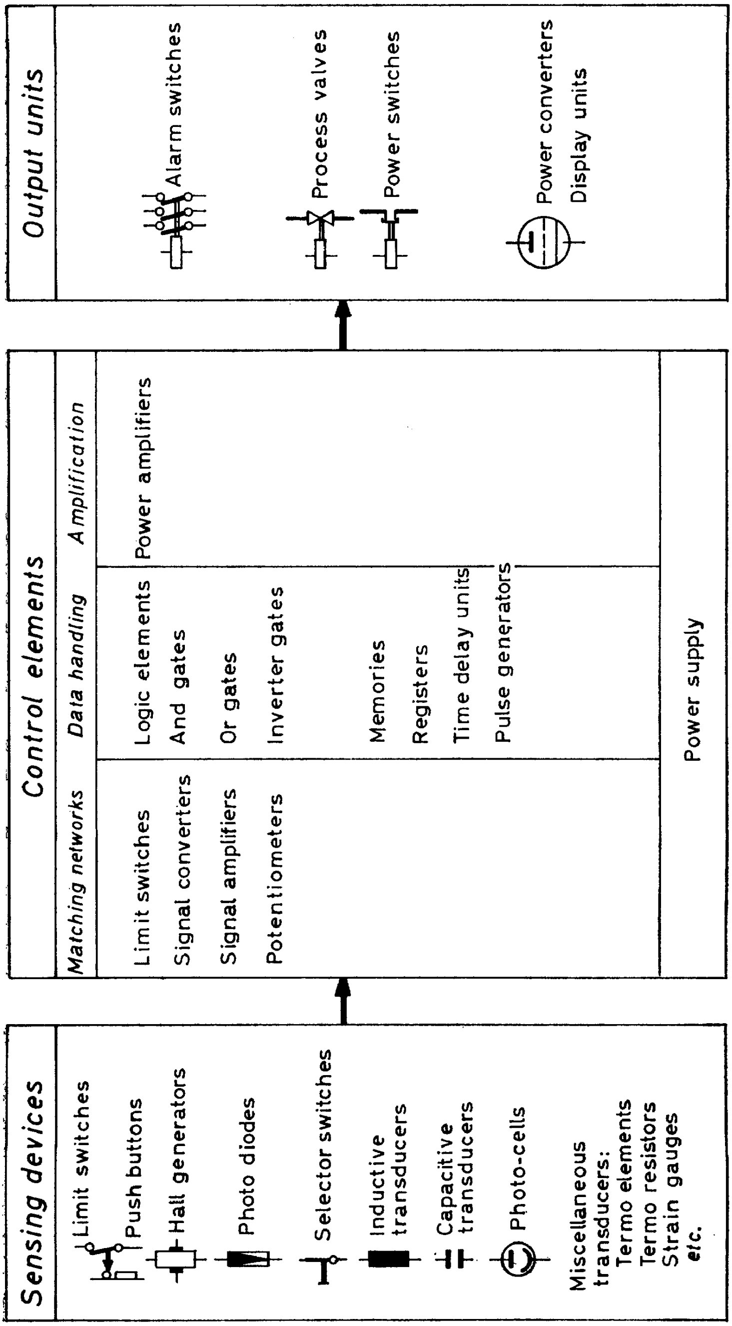

Figure 37. The main units of a logic control system

with these elements is not great. We have a few experimental installations in operation, and preliminary results are encouraging.

Quality measuring instruments are being developed rapidly. For many products in the chemical industry it is not possible to give exact specifications of what really are customers' requirements. In this connection one may think of the final specifications of products like alcoholic beverages and synthetic fabrics.

If over-all control is necessary, we must be able to measure the composition of products, the yield of reactors, over-all operating economy and some kind of product property which satisfies customers' requirements. In spite of the ever-increasing number of quality measuring instruments which have been brought on the market, most chemical industries must still do extensive development work in this field.

At the present stage it seems impossible to give a brief survey of the application of such instruments. So many physical and chemical reactions are in practical use for measuring purposes that the mere listing of principle possibilities is a task in itself.

Gas chromatographs and infrared analysers may be the two instruments in most widespread use. They are both very reliable and can be supplied with standard accessories, which permit them to be included in process control loops. In principle they represent two different kinds of instruments as seen from a control engineering point of view. The infrared analyser is a continuous instrument, or at least it works with such a high sampling frequency that for most purposes it can be considered as a continuous instrument. The chromatograph is a sampling device and some additional kind of clamping circuit is necessary in order to tie it into a control system.

Some process analysers may have a rather low sampling frequency, or large time constants and delays. In my own experience this drawback in most cases can be circumvented because process analysers are usually required only to correct slow changes in the process. Fast disturbances will be taken care of by conventional instruments and controllers.

Safety systems will require a different approach.

It is always important to get a correct sample from the process stream brought to the detecting device. Quite a few precautions will be found necessary in this connection, and some general advice will be found in the literature[24, 25].

In many cases operating personnel can be assisted by computed process variables. As an illustration some examples can be mentioned. In a batch reactor it may be possible from measured heat balance to compute the amount of reacted material. In a boiler, temperature and flow measurement can be used to compute boiler efficiency. In a few cases where the measurement of yield in a chemical reactor is difficult to perform, we have used this technique with good results. Usually it will not be possible to drop the final measurements completely, but they can be performed at a greatly reduced frequency. *Figure 38* shows how the readily performed pH measurement at the last stage of a neutralization process can be used to control acid contents in the first stage where automatic titration normally would have been required.

It will be clear from what has been said up till now that it is fairly common in industry to perform mathematical operations with conventional instruments. Most of these applications make use of analogue type instruments. It is, however, usual to connect computer control with the application of digital computers for the supervision of rather complicated processes. It has been indicated that a computer will usually not be able to improve operating economy by more than 5 per cent, referred to total plant cost, and at least 0·5 per cent. Some reports give 1 per cent as a likely average[7, 23]. A process computer installation may cost £50,000–100,000. Based on such figures and a required return on investments, rough calculations can be made about the size of plant where computers can be applied.

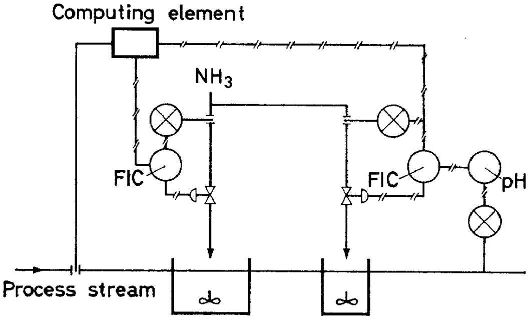

Figure 38. Control of neutralization process

According to the literature, something like 50 digital computers have been installed for the supervision of chemical processes. Most installations have been planned in intimate co-operation between the computer producer and process specialists who know the plant intimately.

In many cases one will find that the process data needed for computer control are not readily available. The following procedure has therefore been suggested: A rather brief feasibility study should be sufficient to indicate if there is a sound possibility of utilizing a computer for a given plant. The computer should then be procured and used as an analysing tool to get the necessary process data. It can right from the start take over such routine work as data logging. The over-all computer control can then be expanded as information becomes available. This philosophy seems appropriate on an existing plant where the computer control will be executed as set-point variations on existing instruments.

The reliability of modern computers is so high that it is feasible to introduce direct computer control, where the computer also takes over the function of the traditional process regulator. Computers can be made available with a downtime not exceeding 2–5 hours per year, which should be sufficient for most process applications. There is still much work to be done to get a set of consistent specifications for components designed to work in such systems. This question will, however, without doubt be worked out in co-operation between computer and component manufacturers and the user.

The important thing for this survey is that computer control has been demonstrated to be a practical industrial proposition. It is stated that quality of control has been improved, and it has been possible to demonstrate acceptable write-off time for the computer installation. It is, however, by no means likely that the technique has found its future form. What has happened up till now is that its feasibility has been demonstrated. Future work will concentrate on the structure of computer control. There will also be an interplay between process design and computer design. As we learn more about processes, we will be able to write better programmes for the computers.

It has been maintained that a well designed process does not need a computer for its control. I hardly think that this view is correct. It seems that industrial processes get more and more critical as construction materials are used at their limits. For this reason automatic control becomes more and more necessary.

To-day we tend to think in terms of rather simple control structures for computer control. Most applications to-day have what could be designated as a diagonal control matrix, meaning that we prefer to let one output influence one input. As we complete our control strategy, we will be able to make practical use of more complex control matrices. This kind of control is necessary if we want to realize optimal control. It is very difficult to visualize how such systems can be built for the control of complex systems without the use of digital computers. I therefore think it is safe to say that the digital computers have entered the control picture in order to stay, but we must be prepared to see great modifications in the design, both of the computer itself and its peripheral equipment.

It has been interesting to note that on-line computers have been taken more into use in U.S.A. and U.K. than in Germany. There may be many explanations to this. German chemical industry has traditionally concentrated much work on the development of better instruments. It seems that the philosophy has been that for some years to come it is more important to use available talent to develop new instruments and make better use of components that are already available than to take part in the development of new computational techniques for continuous optimization of large systems. At the same time work has gone on to obtain a better foundation for the formulation of mathematical models for processes. If it is a question of priority, I feel that the computer control will have to come at the end in this picture.

CONCLUSION

Process control has become an important branch of Control Engineering. A sound theoretical basis exists for the design of simpler control systems. Instruments, controllers, valves and various auxiliary equipment are able to satisfy most industrial requirements.

Control systems design requires a fairly extensive knowledge of the dynamic behaviour of processes. Control engineers have taken active part in the development of more powerful methods—experimental and theoretical—for the exploration of process dynamics. Information is available for the formulation of mathematical models for a large selection of processes and process equipment. Analogue and digital computers have proved useful for the design of process plants with associated control systems. Computing elements, special purpose computers and digital computers have been taken into use for the automatic supervision of processes.

One of the most important prerequisites for further progress is the development of still more accurate measuring devices from flowmeters to quality measuring instruments. These instruments will form the hardware basis for future efforts to realize optimal production processes.

Extensive work is required to check further the validity of mathematical models. This holds true especially for chemical reactions, and when a more detailed knowledge of process mechanisms as diffusion is required.

Extensive development work is required to bring industry into the position to evaluate the practical consequences of advanced control theory.

Computers must be better adapted to process requirements for optimal on-line control. An easily applicable theory for multi-variable control systems is still to be developed. This theory may in itself influence computer and process design. The design and control of process production systems has to be looked upon as a whole, making necessary full co-operation between chemists, physicists, chemical engineers, applied mathematicians and control engineers. Co-operation between industry and research centres may in many cases be required to assemble the necessary talent.

The control engineer who wants to specialize in process control must include chemical engineering and reaction engineering in his curriculum. In addition he will need a thorough grinding in mathematical analysis, applied mathematics and the use of analogue and digital computers.

A control engineer trained along these lines should be in a position to make important contributions to further industrial progress. I think there is much enthusiasm among the students of control engineering. It is my hope that industry in the future can afford the research and development projects which will accelerate progress and give our young scientists the challenge they need to preserve their enthusiasm.

The author wants to thank his co-workers in the Research Council and Norsk Hydro for the assistance they have given in the preparation of this paper.

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