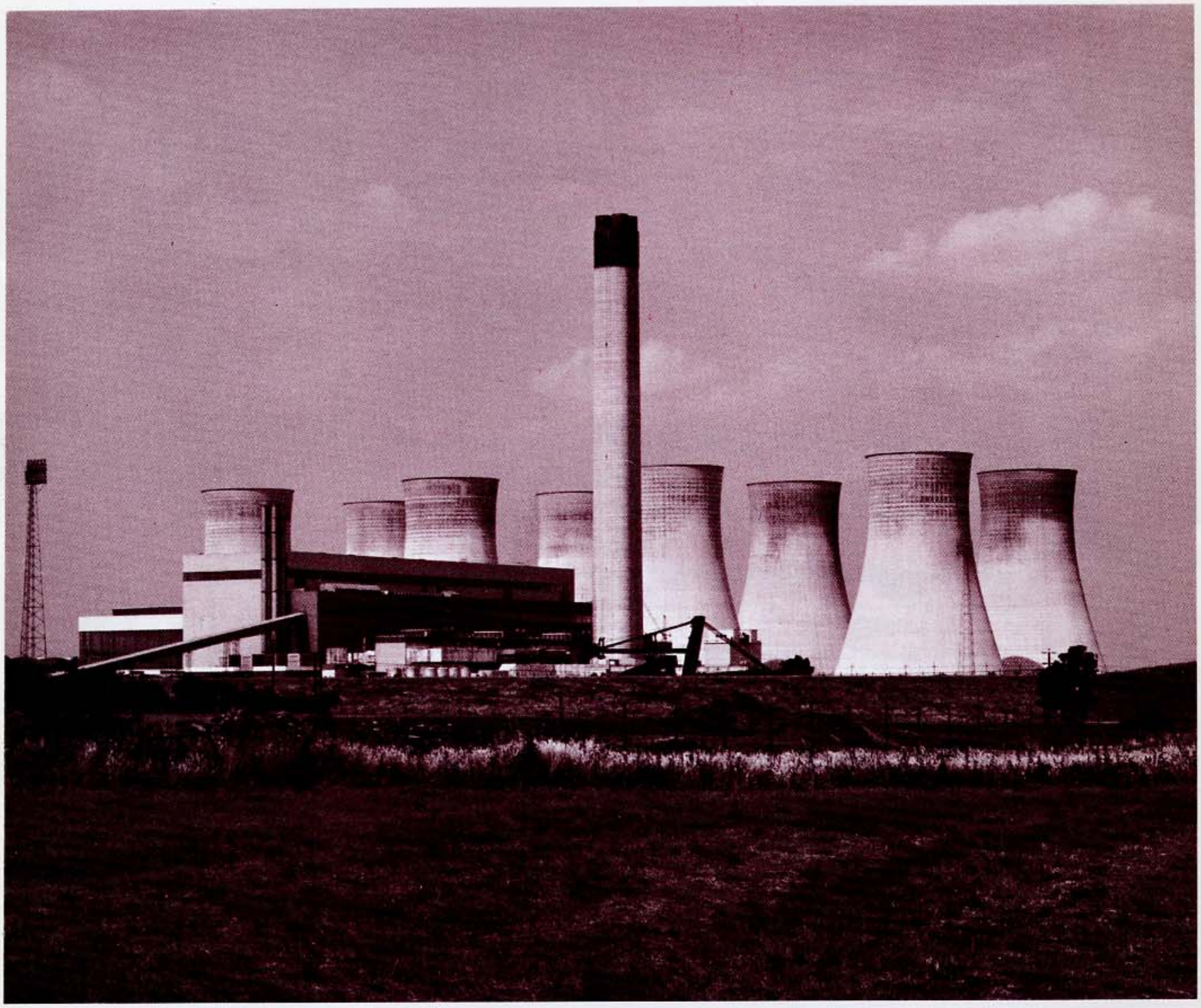
APPLICATION NOTE 98–1

Noise at Work

Model 3722A aids design of process control systems



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Process control systems

Process control systems are to be found in every branch of industry — chemical, petroleum, plastics, steel, and so on. Regardless of application, all closed-loop control systems have a common aim; namely, to monitor continuously a parameter (temperature, flow, thickness, etc.) and to maintain that parameter at some desired value.

The problem

Suppose a new design of, say, an oil refining plant were proposed. The first obvious step would be to define the type and production capacity of the new plant, and to draw up a schematic. In earlier years, this would have been followed by the construction of a static scale model and, finally, the real-life installation. Since a static model is concerned only with physical layout, it tells nothing of the plant's likely behaviour: but to construct a complete working model of the plant would be prohibitively time consuming and expensive — in any event, could one be certain that a model faithfully reproduces all characteristics of a proposed system?

Because the engineer had no reliable data on which to base his design, there was no alternative to the trial and error method — build the real-life system first and then re-design as necessary to optimise performance.

Mathematical models

The approach today, however, is to build a *mathematical* model of the proposed system with the aid of a computer. Such a model allows manipulation and observation of parameters without involvement in hardware. Secondly, the model can yield results in far less time than would be possible from experiments with the 'real thing' — the larger process control systems have very long time constants (that is, they are slow to respond to change), and experiments on such systems are unavoidably lengthy: in a mathematical model, all time constants can be scaled down, with corresponding savings in experimental time.

A direct outcome of the development of mathematical models has been a better understanding of control systems in general: this will lead to the design of more sophisticated digital and (ultimately) self-adjusting control systems. Further, with an established technique of model construction, it will be possible to evaluate new designs of plant with much greater precision and less expense than before.

How the model is developed

A complete system model would comprise many mathematical terms, each describing the transfer characteristics of a particular component or sub-system. The transfer characteristic (or transfer function) completely defines the component's performance; that is, its response to any arbitrary input. Here is the problem ......

How can we establish the transfer function of each component on the proposed new system?

Typically, this problem can be solved by instrumenting already functioning systems whose components are similar to those projected for the new system. Once the transfer function for each part of the system has been determined, it is a relatively easy matter to construct a mathematical model.

This application note is concerned mainly with methods of finding the transfer function of working systems. Although much simplified, the steam temperature control system described below is typical of the closed-loop servo encountered in large-scale industrial plant.

A typical system

Figure 1 illustrates a simple servo control loop designed to maintain steam temperature at a level demanded by some other sub-system (or hand control) of a boiler system. A change in steam temperature could be demanded as a consequence of, say, a change in steam pressure or rate of fuel combustion (in modern plant, a steam temperature control loop of the type shown would be interconnected with a large number of other sub-systems).

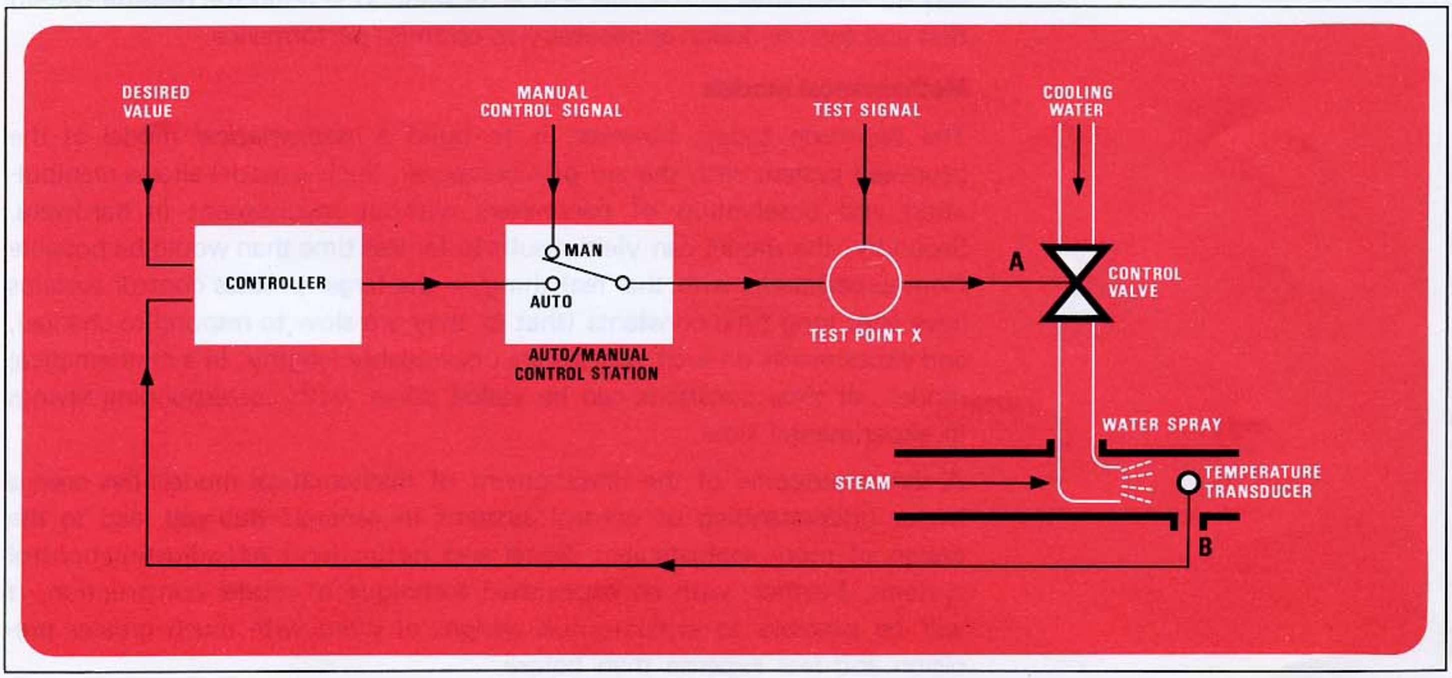

Figure 1. Steam temperature control – a simplified closed-loop system

When the system is in equilibrium, the output from the controller is constant. On detecting a change in the desired value, the controller gives out a signal which causes the valve to adjust the flow of cooling water, as appropriate, to restore the system to equilibrium.

In this system, the unknown section, the transfer function of which is to be found, lies between A and B. How can the transfer function of the unknown section be found? In other words, how can we *identify* the unknown section? Three well-established techniques are reviewed below. In each case, the loop is opened at the auto/manual control station, and a signal is injected at test point X (merely a convenient point of access to the servo loop).

1. Sinusoidal testing

In this method, a sinewave is injected at the point X, and the gain and phase shift introduced by the system is measured between points A and B. The experiment is repeated with a series of different frequencies ranging from very low value up to the point where the gain becomes too small to be measured.

This method is very time consuming when the system time constants are long (in a typical boiler system, for example, they could be in the order of 15 minutes): to obtain complete information, it is necessary to use a family of sinewaves at least some of which must be longer in period than the system's longest time constant.

A second disadvantage is that the sinusoidal signal at B may be buried in noise to the extent that measurements of phase and gain are rendered difficult. This can, of course, be remedied by applying a larger signal at X, but this could lead to undesirably large fluctuations in steam temperature — or whatever parameter the servo system controls. In almost all process control systems, large deviations must be avoided for reasons of safety and prevention of waste (product not to specification). The experimenter must select a compromise between two extremes — namely, (1) an easily detectable signal coupled with unacceptably large parameter fluctuations, and (2) small parameter fluctuations resulting in difficult signal detection.

2. Step testing

The main objection to sinusoidal testing — that of lengthy experimental times — can be overcome by applying a step function instead to the test point. The resulting curve measured at the output from the temperature transmitter contains all the information needed to characterise the system. This method, however, has the disadvantage that steady state conditions in the system are changed by application of the step. Further, the step must be small if the system is not to be driven into a non-linear operating region: as with the sinewave, a small amplitude test signal leads to problems in detecting the response.

3. Pulse testing

The pulse as a test signal overcomes the inherent disadvantages of the step function — namely, the tendency of the step to cause a radical shift in the steady state of the system. A pulse can be thought of as a brief injection of energy, after which the system is allowed to revert to its original steady state. Again, however, it can be difficult to detect that part of the system output due solely to the pulse, unless a large-amplitude pulse is applied.

Summarising: none of the three traditional methods is well adapted to the on-line identification of complex systems for the reason that the response is difficult to detect unless large test signals are applied — with, of course, a disturbing effect on the system's normal functioning.

System identification without disturbing the system

Ideally, the method used to identify the system should employ a test signal smaller in amplitude than the existing background signal in the system, and yet should be capable of extracting the response to the test signal from the background noise.

The technique of cross-correlation provides the answer ......

> *An approximation of the IMPULSE RESPONSE of a linear system can be determined by applying a suitable NOISE signal to the system input, then CROSS-CORRELATING the noise signal with the system output signal.*

Cross-correlation involves continuous multiplication of the two signals, and averaging of the products over a fixed interval of time. The multiplication and averaging process is repeated with various delays between input and output signals, and the averaged products are then plotted against delay time to give an amplitude/time curve corresponding to the impulse response of the system under test.

Here, then, is a technique which can be used to overcome the main disadvantage of conventional pulse testing — the need to apply a large pulse to give a measurable output. The noise test signal can be applied at a ***very low level*** resulting in almost no system disturbance and very small perturbations at the output. Cross-correlation, which is essentially a process of accumulation, builds up the result over a long period of time. Hence, although the perturbations may be very small, a measurable result can be obtained provided that the averaging time is sufficiently long. Background noise in the system will be uncorrelated with the noise test signal, and will therefore be effectively reduced by the correlation process.

A typical experiment

The Central Electricity Generating Board (C.E.G.B.) in Great Britain is engaged on a program of research leading to the design of more efficient

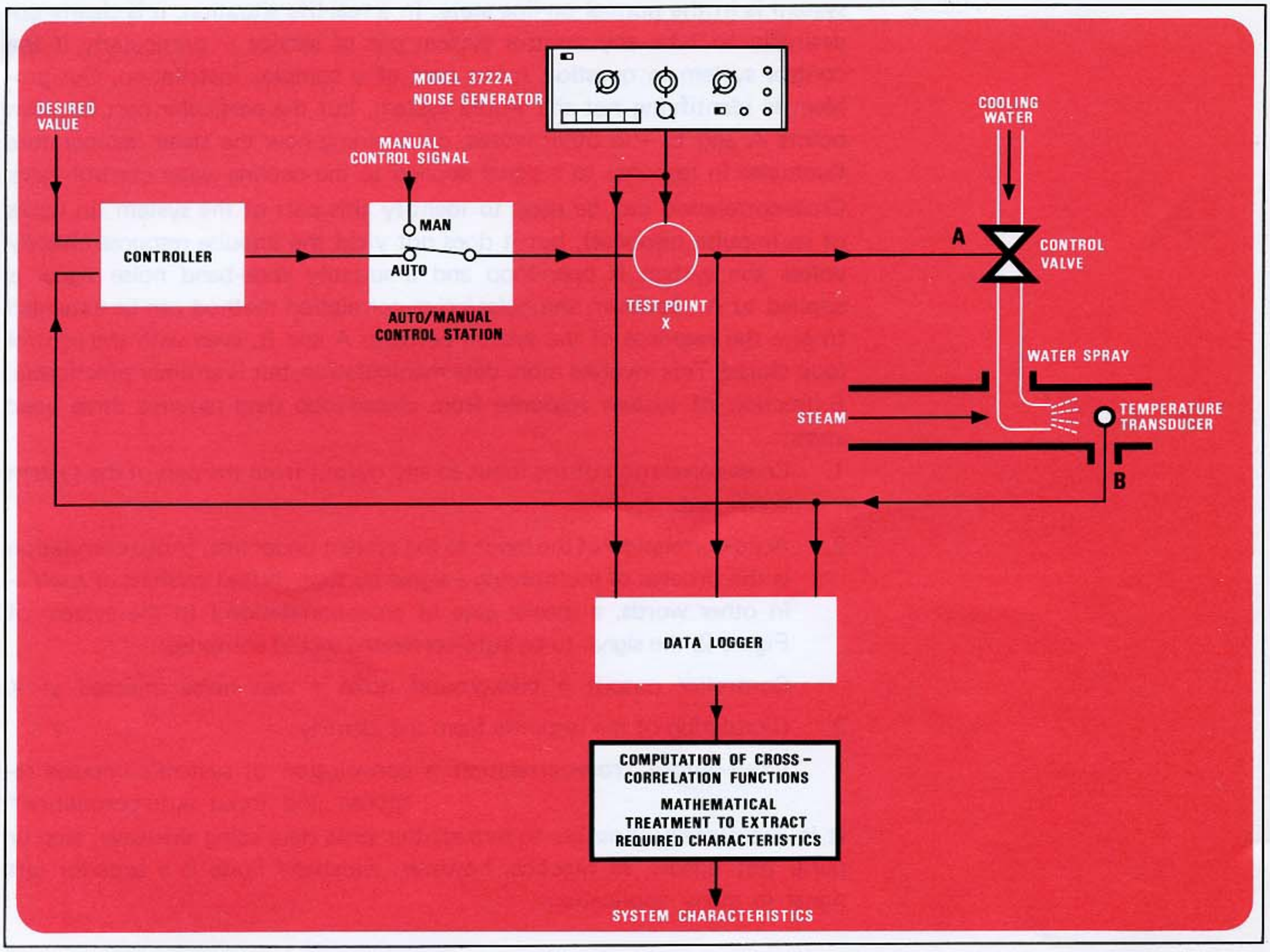

Figure 2. Analyzing data from the steam temperature control system

boilers and related control gear. As part of this program, a 500MW system at Ferrybridge, England, has been specially instrumented. Transducers have been fitted at over 400 points in the boiler system, and their outputs have been brought out to a data logger which, in a typical experiment, records simultaneously some 20 variables.

The noise test signal from the Model 3722A is applied to a suitable test point in the system to be evaluated. Signals from the test point and from other points in the system affected by the noise test signal are recorded on punched tape for subsequent analysis. Cross-correlation and other manipulations of the data are then performed by a specially-programmed digital computer. Each control loop, or sub-system, in the boiler system has been similarly treated, and a mathematical replica of the complete boiler system has been constructed on the basis of the sub-system characteristics thus obtained.

Note that in Figure 2 the control station is shown set to 'auto', that is, the system is in the normal on-line state. In a real-life situation, it is clearly undesirable to take any control system out of service — particularly if the control system in question forms part of a complex installation. Our problem is identifying not the whole system, but the particular part between points A and B — in other words, determining how the steam temperature fluctuates in response to a signal applied to the cooling-water control valve. Cross-correlation can be used to identify this part of the system (in terms of its impulse response), but it does not yield the impulse response ***directly*** unless the system is open-loop and a suitably wide-band noise signal is applied to A. However, the noise/cross-correlation method can be extended to give the response of the system between A and B, even with the control loop closed. This involves more data manipulation, but is entirely practicable. Extraction of system response from closed-loop data requires three basic steps:-

1. Cross-correlation of the input to and output from the part of the system under test.
2. Auto-correlation of the input to the system under test. (Auto-correlation is the process of multiplying a signal by time-shifted versions ***of itself*** — in other words, a special case of cross-correlation.) In the system of Figure 2, the signal to be auto-correlated would comprise:

   Controller output + background noise + test noise injected at X
3. Calculation of the response from the identity:

   Input-output cross-correlation = convolution of system's impulse response and input auto-correlation*

It is, incidentally, possible to extract the same data using sinewave, step or pulse test signals. In practice, however, wideband noise is a superior test signal in many applications.

Hewlett-Packard Model 3722A provides calibrated noise

The noise used as the test signal in system identification work should ideally have a well-defined power spectrum — hence the need for a precision noise generator such as the Hewlett-Packard Model 3722A, which was designed specifically for the type of work outlined above. As a result of its excellent low-frequency performance, this instrument is of particular interest to those concerned with large systems. The ***upper*** cut-off frequency of the noise output is switch-selectable down to 0.00015Hz (***approximately 1 cycle in two hours***) — and further, the power output remains constant, quite independent of the bandwidth selected. The Model 3722A differs from the normal run of commercially available instruments in that it generates pseudo-random noise; that is, an endless repetition of a particular noise sequence, the duration of which can be selected to suit the experiment. Repetitive noise of this type has well-defined, and non-varying properties which make it a very satisfactory test signal for system identification work.

****LEE, Y.W. Statistical Theory of Communication, Wiley 1966.***

HEWLETT hp PACKARD

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