DESIGN OF MACHINERY FOR AUTOMATIC CONTROL

BY

COMMANDER J. I. FERRIER, R.N.

In this article the mental functions of the watchkeeper, e.g. in a boiler room, are analysed in order to show how these must be catered for in machinery and systems which are automatically controlled. It is written in the context of the control systems now at sea and being installed in new construction and does not consider developments either in the type or extent of such controls.

The Man-Machine Combination

The aim, in designing an automatically controlled machinery installation is to dispense with the watchkeeping effort of humans. This does not eliminate the watchkeeping function but transfers it to the machinery itself and its control instruments. Thus, some combination of the characteristics of the machinery and instruments has to equate to those of a trained watchkeeper.

With manually controlled machinery the watchkeeper and his machines (and boilers) combine to act as a working installation which reaches certain levels of performance and efficiency, after the watchkeeper has acquired operating experience. The design of the machinery and systems evidently fixes the extent of training and experience required by an efficient watchkeeper.

One has often heard comment of the kind ' At these revs. she steams herself '. This equals ' Look mummy—no hands '! The reader will recall that the latter phrase refers to a steady operating condition—the former specifies it.

It will perhaps be agreed that the full prowess of the good watchkeeper is only called into play during rapid changes of power, and, further, that such watchkeeping ability is attained only as a result of a great deal of formal training and practical experience.

An arrangement of automatic controls which has to simulate this prowess is obviously going to be very complex, hence it will be difficult to adjust initially, temperamental in operation and tedious to put right when it goes wrong.

What emerges from all this? Surely the fact that the period of training and experience required to make a watchkeeper efficient, and the complexity of the control system which replaces him are both related directly to the skill required to operate the particular machinery efficiently during rapid power changes, not while steady-steaming.

In our design work we have hitherto concerned ourselves with performance at steady conditions through the power range, paying attention to acceleration of output only as a factor in stressing components.

It is now suggested that elegance and simplicity of control should be sought through study of the time-dependent characteristics of the machinery itself. At present, the principal but subconscious student of these characteristics is the watchkeeper.

The first move then is to look into his brain and discover what he does.

What the Watchkeeper Does

Leaving aside the processes of starting up and shutting down machiney, let us analyse broadly the function of the watchkeeper in controlling machinery during manœuvring and steady steaming.

(*i*) He accepts information about what the machinery is required to do, and also about what it is doing.
(*ii*) If these conditions become out of balance he recognizes the sense and rate of change of unbalance.
(*iii*) During this change he must compare the instantaneous condition with memorized criteria and the predicted level of power balance, if available.
(*iv*) He then decides whether corrective action is going to be necessary.
(*v*) Concurrently he will compute the time lag in bringing the machinery to the new operating condition.
(*vi*) Having decided that some action should be taken he must decide the nature and extent of the suitable corrections.
(*vii*) He must then physically apply them.

Seeing that he may be in control of perhaps six interrelated functions, all of which must be considered together, as above, but each of which has quite a different ability to respond to an alteration of settings, he is a very busy man. His muscular exertions may be considerable, but are insignificant by comparison with the activity of his brain.

How He Trains His Brain

His brain is so clearly the key that we must analyse the nature of its contribution. Firstly, its three forms of operation comprise :—

(*a*) Perception (of information by means of the senses)
(*b*) Memory (the storage of facts learned or observed)
(*c*) Logic (the power of decision based on perception and memory).

In the brain of the watchkeeper these abilities are called into play more or less continuously through his career for three modes of exercise. These may be called static training, dynamic training and dynamic practice (which is watchkeeping).

The static element comprises all the general training and pre-commissioning training concerned with operation of machinery, and the acquisition of familiarity with the layout and location of machinery, systems and control elements, e.g. handwheels, in a ship.

Dynamic training covers the absorption into the memory of experience obtained from actual operation of the machinery, which includes the committing to memory of the response capabilities of the various controlled functions.

Both forms of training admit of the use of memory and logic to establish the correct solutions to complex situations and to commit these solutions to memory.

The Brain on Watch

In actual watchkeeping the faculty of perception is concerned with collecting three types of information, namely, what the machinery is doing, what explicit orders are received which demand alteration to the settings of the machinery, and what warnings are available about potential or imminent alterations to machinery settings.

Of these, the need for the first two is self-evident. What then is the importance of the last? Two reasons present themselves :—

(*i*) The desire to have the time to work out the corrective action to be taken before it has actually to be carried out.

(*ii*) Recognition that the machinery as a whole responds to a forced change with an inescapable time lag and that the different elements of the machinery possess inherent time lags which do not match one with another, e.g. the POM(E) orders ' up one ' only after he has started to speed up the blowers.

The first of these calls both memory and logic into play, the solution established being then deposited in the memory (possibly only for a few seconds).

The second reason calls up the memory since it relies on information stored from previous experience. But what in fact is the nature of this information?

Inertia and Time-Lag

In accelerating a mass towards a new steady state the property which causes a time lag in reaching that state is the inertia of the mass. The information referred to is, therefore, the effect of the inertia which must be overcome between the point of applying the change (e.g. blower throttle handwheel) and the point where the change becomes effective (air pressure at the register). The inertia is not, then, merely the inertia of the machine, but also the inertia of that quantity of the medium with which the machine is concerned, between the machine and the point where the medium is effective (the volume of air from blower outlet to register).

As if this were not enough, the time lag associated with the inertia of any system is apparently variable throughout the power range, for a given percentage change in load, when referred to the movement of the handwheel controlling it. This is most evident, perhaps, in the hand-feeding of a boiler using a feed check valve of traditional design.

A different value of inertia is invariably associated with each control in the system, and each suffers its own degree of variability (referred to the handwheel) through the power range.

In short therefore, the watchkeeper has to manipulate a large assortment of highly variegated and individually variable inertias with complete harmony through any magnitude of transient condition to any new steady state. He must do this without allowing any one element of the system to reach an unacceptable or dangerous condition, even momentarily (e.g. making smoke), and must continue to do so in varying degree for four hours at a time.

Simulating Brain Functions

If one is to substitute an automatic control for the human watchkeeper it is necessary to provide a complete material substitute for the highly sophisticated complex of mental abilities which the human brings to the task—or to compensate in a logical manner for any inability to provide such substitution.

To recall the faculties which the automatic installation must simulate, these are—perception, memory and logic.

Perception

Considering perception first, information about the present settings and output of the machinery, and demands for changing these to meet the needs of other associated machines are provided as measurements, of, for example, pressures and temperatures. The other types of information are not so easy, however, to turn into any kind of measurement and, unfortunately, most of these offer warning or foreknowledge—a message passed over the ships broadcast systems, change in steam noise or of ship noises generally, familiarity with the manœuvring habits of the Captain in approaching a frequented billet.

While it is not physically impossible to measure such information and use it in a control system it is entirely impracticable to do so.

Control instruments are therefore unable to react to changes in condition until such changes have started to occur. The instrument can then start to perceive the sense and trend of the change, and deal with the situation by exercising memory and logic.

Memory

The different kinds of memory which must be provided for embrace the following :

(*a*) Facts relating to the general doctrine of operating machinery, with specialized information peculiar to the design of machinery being controlled

(*b*) Facts concerning the layout and location of machinery, systems and control elements

(*c*) Facts concerning the inertia and time lags associated with each control element.

These three collections of fact are provided in the control system as follows :—

Operating doctrine—in the design of the machinery installation and control system, by decisions on what functions are to be controlled, what quantities to be measured and with what accuracy, what quantities are to be controlled at what value, what mathematical laws are to hold a relationship between any two or more quantities, and what safety arrangements are to be provided.

Layout and location—in the physical location and connection together of the various instruments and control elements in the machinery installation. (An instrument controlling the operating mechanism of a valve ' remembers ' the location of that valve by being connected to it.)

Inertia and time-lags—in the prediction and application of instrument settings which control the operation of the logic elements of the system. Such prediction can only be made with knowledge of the mathematical laws which describe the dynamic behaviour of the type of machine and system concerned, together with information of the actual dynamic behaviour of the particular design of machine and probable behaviour of the associated system. In practice such prediction is never likely to be completely accurate for all elements of an installation, but a good approximation should be obtainable. This provides a starting point for an ordered sequence of trials to obtain the instrument settings which will give the optimum performance. If there is specialized ' know how ' anywhere in the subject of automatic controls it is in this field of prediction wherein hitherto unregarded laws and characteristics are manipulated.

Finally, the *logic*. This is the function of appreciating the significance of information and generating the means of acting on that information. In control instruments this embraces the ability of comparing information perceived with information stored in the memory, e.g. by a setting on the instrument, of deciding that the error between these is significant and lies in a particular sense, and of generating a signal which will influence a control element so as to eliminate that error. Such signals are necessarily, therefore, functions of the magnitude of the error itself. (N.B. The mechanization of this process is the subject of an article in Vol. 7 No. 4 of this *Journal*).

Where the Machinery Designer Comes In

The General Approach

The designer may now ask how all this touches his work. The first necessity here is to find the right mental approach. Considering that the various parts of the system are both interdependent and, almost certainly, unmatched as to inertia effects, it is clear that under even a very small load change interaction will occur between the various elements and machines. With a skilled and experienced watchkeeper the effects of such interaction are calculated in the brain, in terms of the timing, sense and degree of alteration of the various control elements necessary to eliminate such effects. The application of automatic control does not, of itself, eliminate these interactions but can, and does, compensate for them *within reasonable limits*. The extent of compensation required, however, determines the complexity of the control instrumentation and hence affects the reliability of the installation as a whole. Clearly, therefore, if the design of the machinery and the installation, as a whole, takes account of the natural laws influencing its controllability, the part to be played by the control system becomes simpler and accuracy in operation and reliability of the installation will be enhanced.

Thus, to consider the design of a machine in isolation from the installation it will have to live with is illogical. The only valid approach is to regard the installation as a whole and the individual machine (or boiler) as a part of the installation, to which it is bound by immutable laws.

Acceleration and Inertia

The first point for attention is how a particular machinery installation is to be used. What sort of acceleration of effective output must it be capable of to contribute its part to the acceleration required of the installation as a whole? There is plenty of room here for unbalance between the design of the many elements of a set of machinery. This means, of course, that some elements are capable of accelerating their effective output at a higher rate than others—and are therefore over-designed, with the obvious accompanying penalties.

The key quantity is the maximum manœuvring rate of which machinery is required to be—or will in any case be—capable. In the absence of a quantitative operational requirement, this is likely to be decided by one component, e.g. main gearing, and this figure may then be referred to each part of the plant as a design criterion influencing the power/inertia ratio.

Linearity of Controlled Functions

The second point is that it is most desirable to reduce the extent of variability of the inertia discussed above. The aim here should be to linearize the relationship between movement of the control element and the output of the particular machine at the point where this becomes effective.

Conclusion

The reader may feel that all this is over-emphasis of the importance of controllability for its own sake in relation to the steady state performance which has hitherto ruled machinery design. It is suggested, however, that smooth and harmonious behaviour of the machinery itself up and down the power range would be not only a major advance in efficiency and economy of design but incidentally the surest way of reducing to great simplicity the task of the automatic controls—and of the human watchkeeper who may have to take over when the ship is damaged.