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CONTROL SYSTEMS FOR TURBINES AND BOILERS

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The control systems described in this paper apply to typical present-day marine steam turbines and water tube boilers, but similar techniques can also be applied to other marine plants such as gas turbines, diesel engines, cargo pumps, refrigeration plant, etc. The paper describes electronic equipment design suitable for the marine environment, followed by considerations of safety when designing electronic control systems. Finally, the paper investigates some of the problems of tuning control systems, and ends with a discussion of possible future trends in marine automation.

NOMENCLATURE

PT = Pressure transmitter
FT = Flow transmitter
LT = Level transmitter
MT = Water mass transmitter
Rev/min = Revolutions per minute transmitter
Δ = Comparison
S = Pre-set signal
$\% + \int$ = Proportional + Integral controller
$\% + \int + dt$ = Proportional + Integral + Derivative controller
H/A = Hand/Auto station
$\sum$ = Summator
fx = Calibrating amplifier
LSS = Low signal selector
HSS = High signal selector
PU = Positioner
CV = Control valve
CD = Control drive
A = Amplifier
≮ = Minimum limiter
≯ = Maximum limiter
AL = Alarm module

BOILER CONTROLS

There are three main control systems associated with a marine water tube boiler; these are combustion control, feed water control and steam temperature control, and each of these can be divided into sub-systems with air heaters, fuel oil heaters, feed pumps, deaerators, feed heaters, etc. However, in this paper the authors will confine themselves to describing how the three main control systems are built up from a basic understanding of plant behaviour. The requirements of the three main systems are as follows:

a) *Combustion Controls:* To match the energy output of the boiler in the form of steam to main engines and auxiliary plant with the heat input of fuel oil. This must be achieved in a safe and economical manner by matching the combustion air flow to the fuel flow.

b) *Feed Water Control:* To maintain the level of water in the steam drum, at the same time ensuring the highest efficiency and longest life from the plant by regulating the speed of the feed pumps where possible.

c) *Steam Temperature Control:* To maintain the temperature of the boiler superheated steam at the set value.

Although these systems can be discussed separately, they are in fact, highly interactive, and this must be taken into account when designing control systems for modern boiler plant. This interaction must also be taken into account when optimizing the control systems, and the control loop responses must not only consider the particular controlled parameter, but the effect on all other systems.

Adaptation to Match Plant Design

The particular control systems for a boiler must take into account plant design features such as type of burner, air duct arrangement, method of attemperating steam temperature, etc. Burner type and specified turn-down is a further consideration and this will vary for type of ship and particular vessel heat balance calculations, but general guide lines are that VLCC and bulk carriers require about a 15 to 1 turn-down. Container ships with their high-power turbines and small port load often require 45 to 1 and even 90 to 1 turn-down ratios. The types of burner can be split into three main categories:

a) Pressure jet where the relationship between oil pressure at the burner and the oil flow follows a square-law relationship;

b) Steam assisted or external mix atomizing steam burners, which also follow a square-law relationship between oil pressure and oil flow;
and

c) Steam atomized or internal mix atomizing steam types where the relationship between oil pressure to oil flow is very nearly linear.

From a control point of view these facts become important when designing a control system. For example, because of the square-law relationship between pressure and flow, a pressure-jet burner on a 15 to 1 turn-down on flow has a burner pressure turn-down of 225 to 1. To use fuel oil pressure to the burners as

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an index of oil flow is not feasible, as all instruments have specific turn-down limitations and 225 to 1 is generally too much to obtain adequate performance. However, with steam atomized burners, which have a near linear relationship between pressure and flow, the system designer has a choice of using flow or pressure measurement and the decision can be made on other factors.

The problem of instrument selection and suitability is, of course, a very large and complex subject, but the authors in this paper have mentioned this one case to illustrate that at all times control system design has constraints placed on it which must be considered in terms of instrument capability. Sufficient to say that all flow measurements have particular problems when trying to measure large turn-downs, and all measurements have time lags which must be considered when rapid manoeuvring conditions are specified (generally, the lags introduced by temperature measurement are the most significant in this respect).

The design of the feed water control system may be affected by the availability or otherwise of variable-speed feed pumps, and the design of the control valve will certainly be affected, the valve being an integral part of the control system.

Flexibility to Match Plant Performance

It is a requirement that installed control systems shall be flexible enough to cope with the wide variations in performance of individual plant. Marine boilers are often built by different shipyards or boiler makers, and even though built from a standard design the prediction of their detailed characteristics is seldom possible, and not often undertaken. Thus, it is important that there should be ample adjustment in all the control parameters such as amplifier gains, controller proportional bands, integral action times and derivative action times. Ideally the systems should also permit easy extension to more complex control modes, the addition of feed-forward signals to improve response, and the modification of systems.

In some cases it is possible to develop requirements for non-linear characterization of feed-forward and other control signals such as semi-derivative, rate limited, or load characterized. The systems design should be capable of permitting the addition of any such signals either at the design stage or when the plant is being commissioned.

COMBUSTION CONTROL

As already stated, the detail of a combustion control system is largely governed by fuel, type of burner and specific requirements on turn-down and dynamic performance. However, the general principle is that steam pressure is measured, and variations from the set value are used as an indication of changes in heat input required to balance the heat being taken from the boiler as steam. A controller adjusts the fuel and/or air input to reduce the measured pressure error to zero.

The output from this pressure controller can then be used to directly position the fuel oil valve and, via a ratio relay, the air control damper, so that on load changes the fuel and air input will be changed in parallel (see Fig. 1).

However, this basic system has some severe drawbacks that make it unacceptable for all but the simplest applications; the main ones being that to avoid fuel rich conditions the system must operate on high excess air figures (which is undesirable for economic reasons and because it gives back-end corrosion problems); it does not take into account the different dynamic responses of oil and air sub-systems: pressure control is poor and, perhaps most important of all, there is no safety feature built into the system.

Let us now consider how this basic system can be improved. Firstly, to operate on the correct air-flow/fuel-flow curve, it is necessary to measure the flows, and then compare the two signals in an air flow controller, the controller output being used to trim the F.D. demand signal from the master pressure controller, so that the correct fuel air ratio is obtained. This is illustrated in Fig. 2.

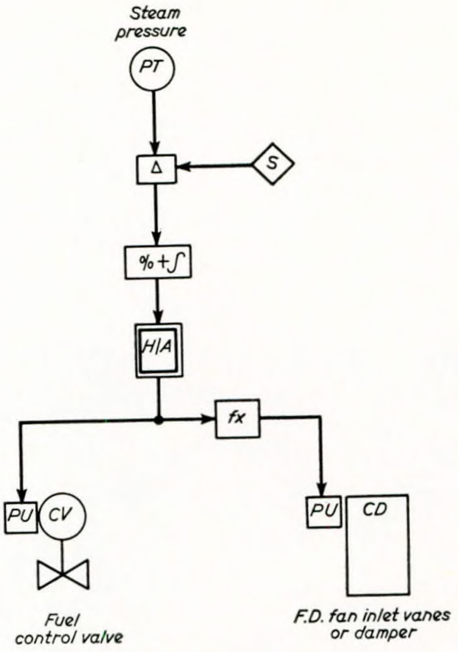

FIG. 1—*Simplified combustion control system*

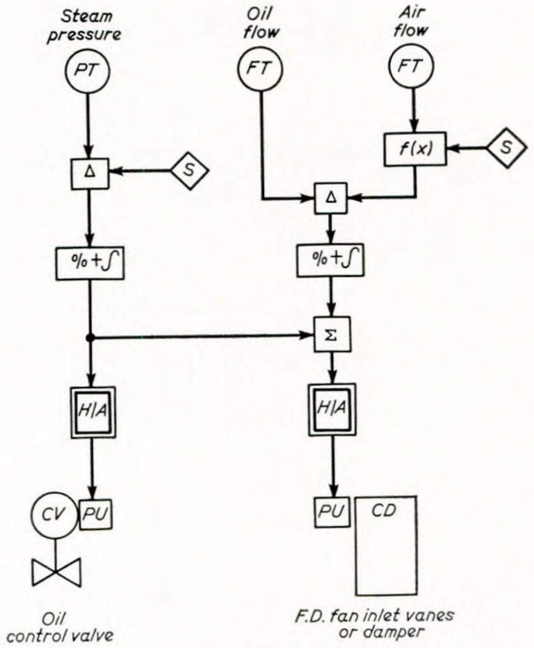

FIG. 2—*Metered combustion control system*

This, however, is an over-simplification of the problem: it assumes that the respective fuel flow and air flow transmitters have been ranged correctly and that the fuel-flow to air-flow relationship is the same at all loads. Further there is no flexibility in the system for varying this relationship. To overcome this a gain-adjusting device (Item f(x) on Fig. 2) is fitted into the air flow signal line, and by varying the gain the relationship between air flow and fuel flow can be adjusted. This adjustment facility is usually brought out to the operator's console.

The relationship between fuel flow and air flow established in the control system is best seen by reference to Figs. 3 and 4.

In Fig. 3 the basic curve "*a*" occurs with the signals from both oil and air flow transmitters matched. The actual relationship used in practice is shown by curve "*b*". If this is now

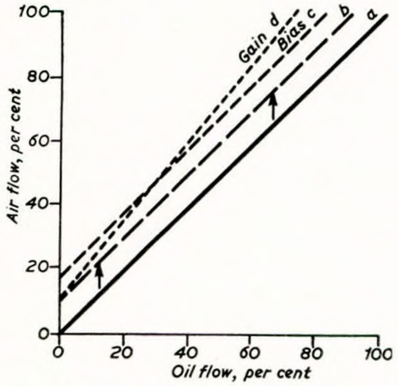

FIG. 3—*Graph oil flow/air flow*

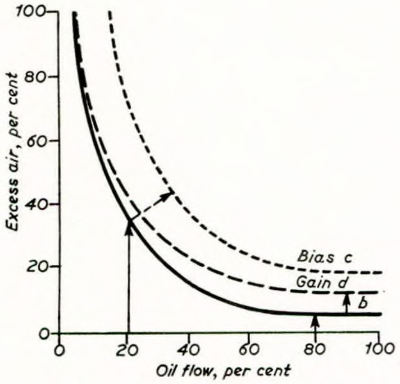

FIG. 4—*Graph excess air load*

expressed in terms of percentage excess air against load the result is curve "*b*" in Fig. 4. We can now see the effect of either bias or gain on the air flow signal line in relation to oil flow and excess air. In Fig. 3, curve "*c*" shows the effect of adding bias to the signal, and the effect on excess air is illustrated in Fig. 4, curve "*c*". The effect of a gain change in the air flow signal line is illustrated by curve "*d*" of Figs. 3 and 4. Thus, with the control system described, with gain adjustment of the air flow signal available to the generators, the effect on fuel/air ratio and excess air can be seen from Figs. 3 and 4.

To improve the combustion control system under transient conditions it is desirable to try and match the response of the air control system to that of the inherently faster fuel system. This can be achieved to some extent by limiting the rate of increasing the fuel oil flow, but not the decrease. Thus on increasing loads the air system responds as fast as the loop dynamics allow, and the response of the oil loop is slowed down to alter slower than the air. However, a better method exists for matching the fuel loop response to that of the air loop. This is known as cross-limiting, illustrated in Fig. 5.

In this arrangement the master demand signal is fed to both air and fuel flow controllers (Items 14 and 8, Fig. 5). The signal to the fuel flow controller passes through a "low signal selector" unit (Item 5) whose second input is the characterized air-flow signal. The master demand to the air flow controller passes via a "high signal selector" (Item 6), the second input being the measured fuel flow. Thus on an increase in load the master demand signal passes to the air flow controller which responds at once, but the signal to the oil flow controller is held by the low signal selector until the air flow signal increases. This system ensures that under boiler load changes, the fuel oil flow is prevented from responding faster than the air flow.

This system guards against a large number of component failures, as it is always demanding air flow to match the measured oil flow, and is limiting the oil flow to the available measured air flow.

FEEDWATER CONTROL SYSTEM

The fundamental requirement of the feedwater control system is to keep the level of water in the drum to within acceptable limits. However, the situation is severely complicated by the fact that the drum is under high pressure, and by the complex nature of the water and steam in the drum. The effect of a sudden increase in steam flow is to reduce the steam pressure in the drum, and this has the immediate effect of *increasing* drum water level because of the reduction in saturation temperature and the consequent sudden ebullition of flash steam. A secondary factor contributing to the same transient effect is the increase in evaporation rate due to the increase in temperature differential (and hence the heat transfer) between the water in the tubes and the gas surrounding them, this increase again being due to the reduction in saturation temperature. The combined effect is known as "swell" and since it contributes a 180° phase shift to the system response it can render simple level control difficult. On a decrease in boiler load the opposite effect to "swell" occurs and is known as "shrinkage". A further factor which adds to the problem of level control is the relatively small size of marine boiler drums, and the corresponding small mass of water in the boiler. With this in mind it is possible to appreciate some of the problems in controlling boiler water level effectively.

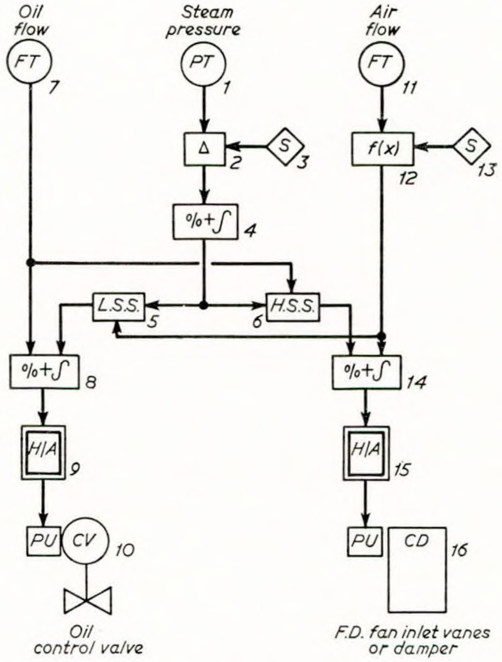

FIG. 5—*Cross-limited combustion control system*

The basic level control is a single-element system, illustrated in Fig. 6, comprising a drum level transmitter, controller, hand/auto station and feedwater control valve. With this system a change in water level from set point will cause the level controller output to move in the correct sense to restore the level to set point by repositioning the feedwater control valve.

However, due to the swell or shrinkage effect of drum boilers, this initial change in drum level is not representative of the long-term requirements of feedwater into the boiler, i.e. on an increase in steam flow, the measured water level increases and the single-element control system actually shuts in the feedwater valve, whereas an increase in feedwater flow is required. On boilers which are required to change load rapidly relative to their dynamic behaviour the single-element level control system is inadequate and more sophisticated control is required.

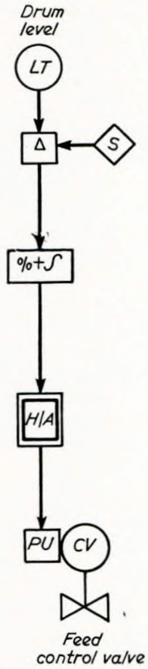

FIG. 6—*Single element level control system*

Working on the assumption that the feedwater into the boiler must equal the steam flow out, we can use a steam flow measurement to position the feedwater control valve, which can be characterized to give a known flow for a set position. This steam-flow signal can then be modified by the output from a level controller to correct for long-term errors in measurement, leakages, boiler blow-down, etc. This is known as a two-element system and is illustrated in Fig. 7. However, this system is very susceptible to interaction from the boiler feed pumps and does not fully meet the actual dynamic requirements to maintain optimum drum level.

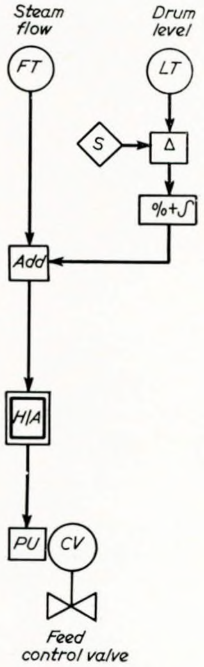

FIG. 7—*Two element level control system*

An alternative to the two-element system is the mass/level method of drum level control(1). This is illustrated in Fig. 8.

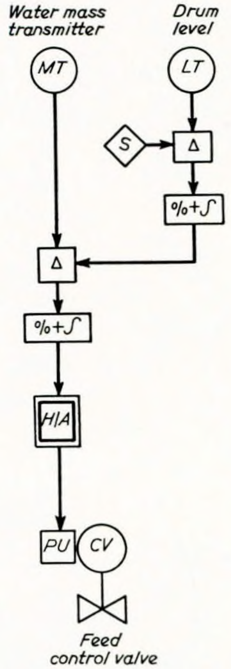

FIG. 8—*Mass/level control system*

The control system is based on measuring the total mass of water in the boiler and positioning the feed valve to maintain this constant, a trim from the drum level controller being used to restore drum level to the desired datum. The mass level control alone would result in a different level according to the boiler load, but this could be a desirable effect, with the controlled drum level being increased at higher boiler load. Whether mass control on its own will be satisfactory will depend on particular boiler design.

Experience has shown that these systems can be improved by using a three-element control system, illustrated in Fig. 9,

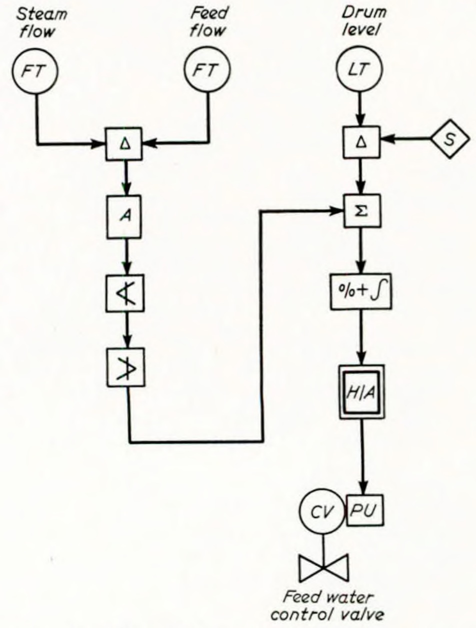

FIG. 9—*Three element level control system*

which relies on a measurement of feedwater flow as well as steam flow and drum water level. There are several variants of this arrangement, the system described being one which achieves very good results in practice. In this system the basic control is from the relation of steam flow to feedwater flow. In closed systems the feedwater flow will equal the steam flow when the system is in equilibrium. The two flow signals are, therefore, compared in a difference module and provided they are equal (as they should be at steady load) the output of this module is added to the desired value of water level in the drum. This signal is compared in the proportional-plus-integral controller with the measured value of water level detected by the level transmitter. Any deviation between the measured value and desired value plus the difference between steam and feed flows will cause the controller to adjust the feed valve position in the appropriate direction to restore the level.

Should steam flow exceed feed flow (as when increasing load) the difference relay output will call for a higher drum level, thus offsetting the effect of the "swell" which would otherwise cause the level controller to close the feed valve.

Similarly, should steam flow be reduced below feed flow (as when decreasing load), the difference module calls for a low level and offsets the effect of "shrinkage" which would otherwise cause the feed valve to be opened.

In both instances, of course, when the load stabilizes at the new level the feed flow will come into line with the steam flow and the difference module output added to desired level signal will call for the normal desired level.

A further advantage of this system is that any variations in feedwater supply pressure to the valve, causing change in water flow, will be immediately detected by the flowmeter and the valve will be repositioned to maintain the proper water flow before this affects tne level in the boiler drum. By suitable ranging of the steam and feed flow signals it is possible to build in a programmed set point for level depending on load, the desired level being higher at high loads. Further improved results are obtained by building into the system high and low signal limits on the output of the steam/feed amplifier. This enables optimum setting of the system to take into account boiler dynamics under the most violent manoeuvres.

STEAM TEMPERATURE CONTROLS

Boilers are designed to give a fairly flat outlet temperature/load characteristic once the design steam temperature has been reached. However, control is still required and is usually achieved by means of a drum attemperator, or spray water attemperator. Either method presents the control system designer with the same problems, namely the relatively long time constants involved. Because of these lags a single-element temperature control system, illustrated in Fig. 10, relying only on a measurement of final steam temperature into a controller which positions either a proportioning valve or a spray valve, is somewhat difficult to set up to obtain satisfactory temperature control, and can permit quite large temperature deviations during rapid load changes.

A method of overcoming the lags in the superheater is to employ a derivative term on the temperature controller. This has the effect of amplifying the rate-of-change of temperature and can to some extent anticipate temperature swings and position the attemperating valve to counteract this tendency.

Further improvement can be made by employing cascade and feed-forward techniques. The choice of final system depends on the boiler characteristics and the specification of final requirements, especially relating to acceptable temperature swings.

TURBINE MANOEUVRING CONTROLS

The requirement for this system is to vary the speed of the main turbine in response to demands from the bridge telegraph taking into account constraints such as a limit on rate-of-change of speed, boiler drum water level, etc.

The system can be divided into two basic parts, the first being the bridge/engine-room link, and the second the turbine speed-control system. The bridge/engine-room link can be supplied to suit the requirements of shipbuilder or ship owner, and the final result is a demand for engine revolutions into the turbine speed control system. Considering the ahead control loop only, this demand signal is compared with a measured value of shaft revolutions, and the controller output fed via a hand/auto station to a power amplifier which adjusts the actuator controlling the entry of steam into the ahead stage of the turbine. This final actuator arrangement will, of course, vary according to turbine design and the manufacturer's practice.

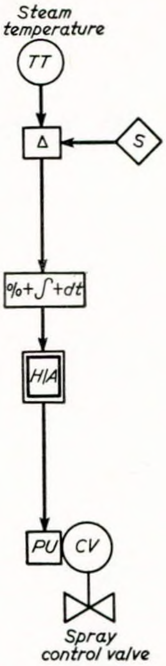

FIG. 10—*Single element temperature control system*

This basic arrangement is illustrated in Fig. 11. It can be improved and built up to include various features depending on the specific requirement of each installation. Among these are the following, which are illustrated in Fig. 12.

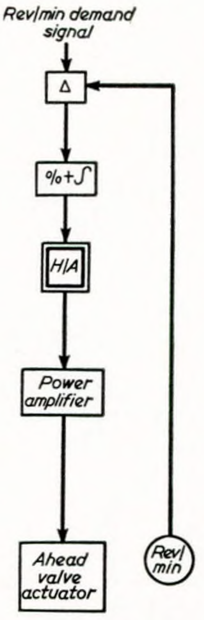

FIG. 11—*Basic rev/min control system*

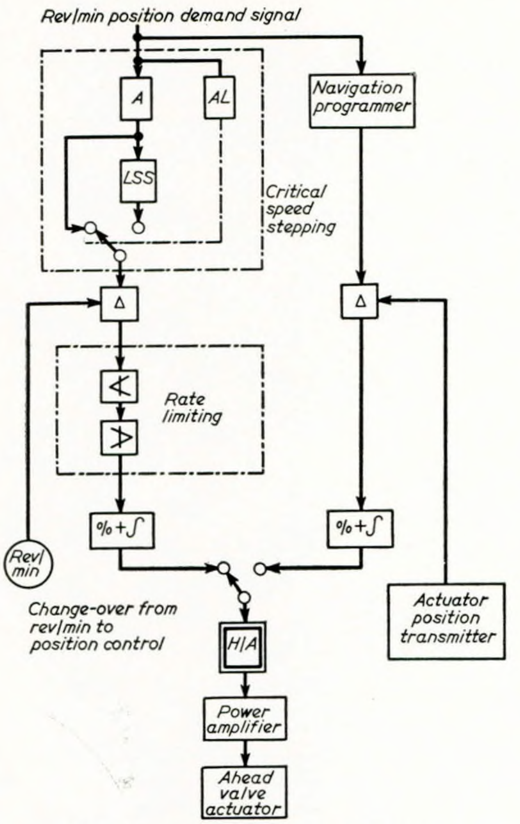

FIG. 12—*Manoeuvring control system*

Rate Limiter

This is required to limit the rate-of-change of the turbine to constraints such as turbine design limitations, boiler characteristics and gearing torque limitations. This can be achieved by suitable adjustment of the speed controller proportional and integral terms, and by limiting the maximum deviation between the desired and measured revolutions. The smaller this allowable deviation, the slower the rate-of-change in controller output, and this, of course, will give slower movement of the ahead steam-valve actuator and the corresponding rate-of-change of shaft revolutions.

Critical Speed Stepping

Some vessels have a critical speed, and to prevent continuous operation of the turbine over this speed range the demand signal for revolutions into the speed controller passes through a signal blocking arrangement that prevents a demand for revolutions within this critical speed range. This ensures that the turbine does not operate continuously within the critical speed, but will accelerate through this speed range.

Full Away Programmer

This unit provides for accelerating the ship's revolutions from the full-ahead to the full-away conditions, this taking typically one hour. The unit must have built-in arrangements that allow, under normal conditions, for transfer from full-away to full-ahead at a controlled rate, but which permit acceleration through this should emergency maneouvres be required.

Full Away Cut Off

The manoeuvring control system previously described relies on shaft revolutions to close the loop. However, if this was used during full-away conditions variations in sea state will cause slight movement in the revolutions, the control system will cause the ahead steam control valve to modulate to correct for these variations which in turn will cause the boiler firing rate to change to meet this demand. For the peace of mind of ships' staff and to save wear and tear on equipment it is desirable to have steady conditions under full away and to achieve this, control of the turbine is switched from revolution control to manoeuvring valve position control, thus giving more stable conditions on the boiler and turbine.

TURBINE BLASTING LOGIC

When stopped during manoeuvring or standby conditions in port it is necessary to roll the turbine at regular intervals, to prevent distortion of the turbine rotor. This can, of course, be done by the operating staff either on the bridge or in the engine room. However, it can readily be built into the control system, to automatically blast the turbine alternately ahead and astern should the shaft remain stationary for a set time (normally given as three minutes).

EQUIPMENT DESIGN

From the above descriptions of boiler and turbine control systems it can be appreciated that the actual equipment design required to meet the wide requirements must be flexible in its application, easy to use and easy to maintain. From an economic consideration the systems must be built up from standard units. The authors will now proceed to describe and specify the requirements for such equipment.

The very nature of marine plant will impose certain conditions which have a direct bearing on the design of all equipment used therein. The factors are:

a) Arduous environment: vibration, attitude changes, temperature, humidity and potentially high electrical interference;
b) The long service life of a ship, its high capital cost and the very fact that it is a ship, and hence often very far from service centres, imply both that the equipment and systems are reliable and fail-safe, and that the spare parts are available for the whole economic life of the vessel, often twenty years or more.
c) The fact that equipment must be maintained by ships' engineers who are often not trained as electronics engineers.

These factors, in turn, lead to a set of design specifications which is quite definite, and which must be followed if satisfactory operation is to be achieved.

1) The equipment must be able to survive the environmental conditions.
2) The equipment and systems must have the highest possible reliability.
3) Installation must be simple.
4) Maintenance procedures must be simple, yet thorough.
5) No failure may give rise to unsafe conditions.
6) Manual control facilities should be provided to back up the automatic systems.
7) Any failure must be easily detectable and quickly repairable.
8) Sufficient stocks of spare parts should be maintained on board ship.
9) Components must be easily available and designs should be capable of accommodating near substitutes.
10) Design of operator interface equipment must be based on ergonomic concepts—based firstly on safety, secondly on ease of operation and thirdly on speed of putting plant on line particularly under conditions of stress.
11) The equipment and systems design should be such that the best possible performance can be obtained from the plant.
12) The equipment and systems should permit flexibility of design and modification to match both predicted and unpredictable plant performance.
13) No serious deterioration or drift of equipment or system performance is permissible.

The way in which these requirements have influenced equipment design is illustrated by the following sections. The examples given here are merely illustrations of typical devices and systems: they do not form a comprehensive summary of all the available techniques.

Transmitters

These would be located conveniently close to the sensing point, and in an accessible position. The transmitters are connected to their sensing points by small-bore "impulse pipes", with equalizing, shut-off and blow-down valves (if fitted) being positioned near to the transmitter.

It is sometimes convenient to group some transmitters and these would be mounted on a single plate; this arrangement eases installation, and aids in the running of cables. Owing to the fact that a marine engine room is an electrically noisy environment, particular care must be taken in cable routing, screening and earthing.

Temperature transmitters generally involve thermocouples or resistance-thermometers inserted directly into the pipelines or ducts, with amplifiers housed in the equipment racks in the control room. To avoid the running of compensating cables over long distances, local cold junction boxes are employed, and standard signal cable connected to equipment racks.

Signal Ranges

Because of the long transmission distances, it is attractive to use current-generator concepts for signals between transmitters and the control equipment. The signal is a *current* whose magnitude is proportional to the measured variable. The resistance, or any variation in the resistance of the cable, therefore, has no effect on the transmitted signal. If voltage signals are used, it would be necessary to calibrate the system against cable resistances, and to ensure that the current flows are so small that variations in the cable resistance are unlikely to affect the accuracy of the system. This would imply low-energy inputs to the various devices, which would make the system noise-prone and would demand particularly careful screening and earthing of inputs.

The use of current-generator concepts not only eliminates the need for lead-wire compensation, but also gives a system which is inherently less noise-prone than a voltage-based system.

The cost of the cable installation can be reduced by using what is known as a "two-wire" concept in which the power for the transmitter is fed via the same wires that carry the signal information in the form of a current. Without this technique it would be necessary to run three additional wires (live, neutral and earth) to each transmitter, since for safety reasons the transmitter must be powered from the same fuse that feeds the related control system. Since power wires are best segregated from the signal wires to avoid possible interference problems, the cost of the cable installation is considerably increased.

For all these reasons, and others, the most popular signal range nowadays is 4–20 mA. The "live-zero" of 4 mA permits the transmitter to be powered from the signal wires, and at the same time allows the use of monitoring techniques to guard against breakage of the signal connexions. The comparatively high level signals also improve interference rejection. A further benefit is that the transmitter can be used in hazardous areas (flammable gases, etc.) since no power source is present in the local mechanism (provided the necessary barrier units and stabilized power units are used).

Now, the signals *inside the equipment cubicles* may be in any desired range: shielding of the cubicles avoids interference problems, and the transmission distances are short. Thus, it is common to convert the incoming signals to a voltage range or to another current range (such as 1–5 V or 0–10 mA), which permits easy signal manipulation.

Typical Transmitters

Figures 13 and 14 show typical transmitters for, respectively, pressure and differential-pressure.

The first uses a Bellows mechanism to produce an electronic output signal via an inductive interface.

The differential-pressure transmitter uses capacitive techniques to measure small movements of a sensing diaphragm.

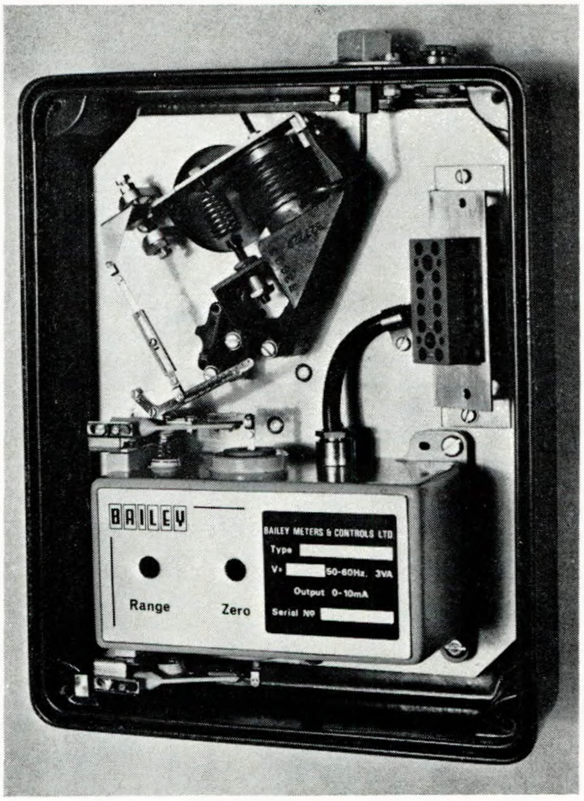

FIG. 13—*Typical pressure transmitter*

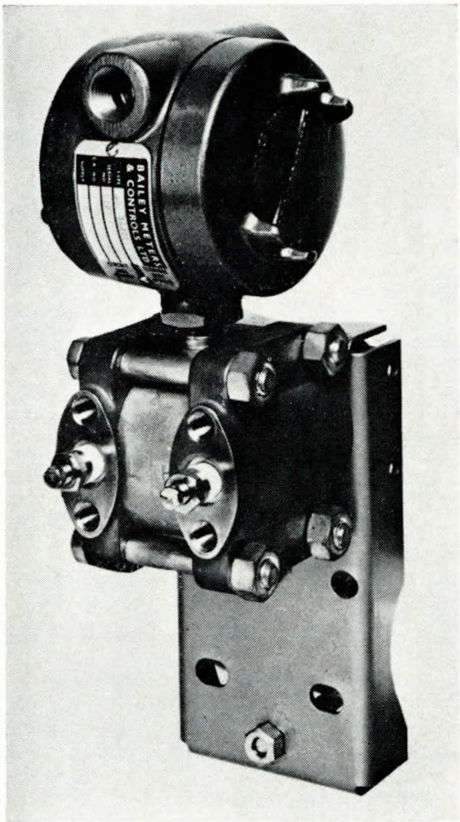

FIG. 14—*Typical differential pressure transmitter*

The process fluid is isolated from the sensing diaphragm by isolating diaphragms, the forces being transmitted via a silicone fluid. The capacitive variation is used to control the transmitted 4–20 mA signal. Since the movement of the sensing diaphragm is small (0·1 mm in either direction), the problems of venting and/or draining the impulse lines are largely obviated, as are expansion vessels, seal pots and reservoirs.

Controllers

Conventional controllers having continuous analogue output signals require special procedures to be followed when transferring between the hand and auto control modes. Since the controller output signal will not necessarily be equal to the manual control signal at the instant of transfer, one or other of these signals will have to be adjusted before transfer if a transient disturbance is not to be injected into the plant at the instant of transfer. Controllers of this type were nevertheless used extensively in marine and land-based installations until the present decade, when it became obvious that some other system was necessary in order to improve the speed of putting plant on line, and to interface with sequence control and computer-supervised systems.

For these reasons, a controller was developed which had a non-position-conscious output, and this is shown in principle in Fig. 15.

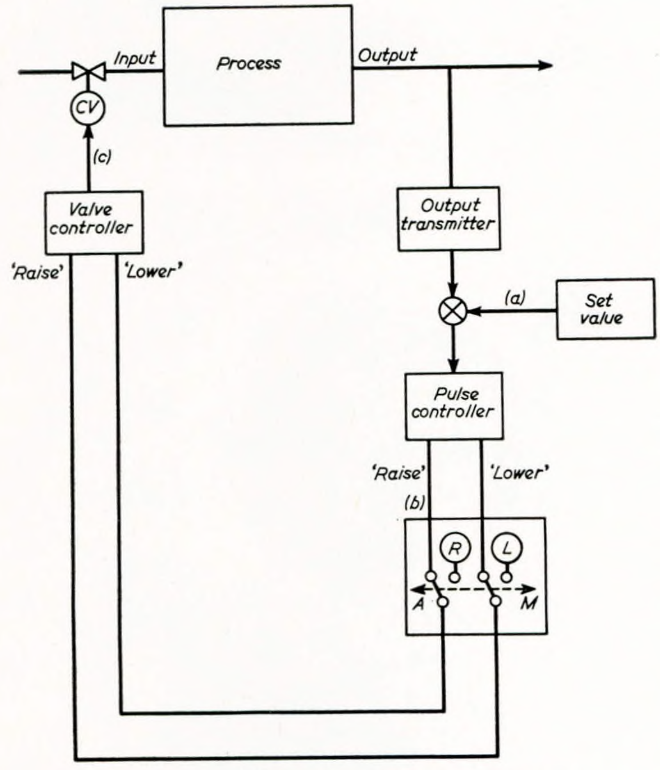

FIG. 15—*Graphical representation of pulse control loop*

Because the output of this controller is "raise/lower" commands in the form of pulses, it is referred to as a *pulse controller*.

The Pulse Controller

Figure 15 shows the operation of this controller in a simple loop, while the operation of the loop is shown in graphical, time-based form in Fig. 16. It is clear that a step change in the set-value signal causes (a) the appearance of a broad, constant-amplitude pulse at the controller output, (b) a train of narrow pulses of the same amplitude. Upon receipt of any pulse, the actuator moves at a constant velocity for as long as the pulse persists.

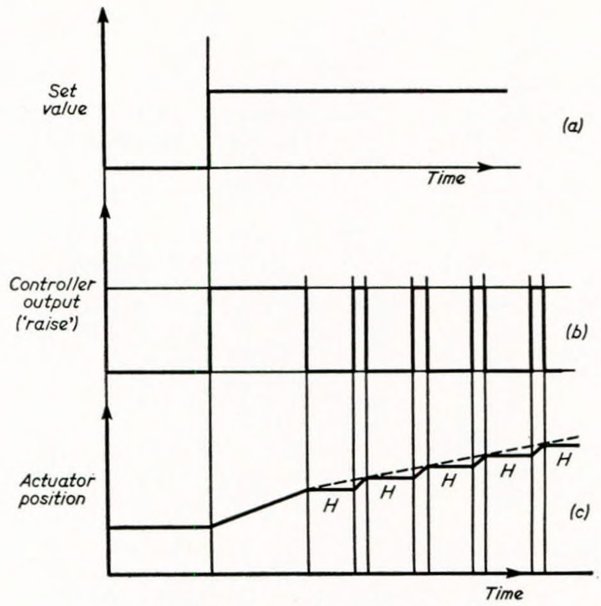

FIG. 16—*Schematic of a pulse control loop*

Thus, the first broad pulse moves the actuator a certain amount, after which time the shorter pulses move the actuator in small steps. This is exactly analogous to the response of a conventional controller and actuator where a certain movement—dictated by the controller proportional band—is followed by a further gradual movement dictated by the integral-action time of the controller. Now, since the actuator responds only to raise/lower demand signals, the absence of such signals causes it to hold the last demanded position. Transfer to manual control is thus simple, since it merely requires a switch which interrupts the controller signals—substituting for them raise/lower commands from push buttons on the hand/auto station. Transfer back to "auto" control is effected in a similar manner.

Because of this inherent bumpless-transfer capability, this mode of control lends itself particularly to sequence control and computer-supervised systems where the loops are switched off and on-line, and manipulated by other equipments.

If a controller is used in a system where some integration process is necessary in order to feed succeeding control sub-loops, a "solid-state memory" is used.

This is basically a 1024-step digital memory followed by a digital-to-analogue converter. The memory is updated by incremental input signals, a "raise" pulse increasing the count in the store, a "lower" pulse decreasing the count. By altering the frequency of the internal clock generator, the sweep time of the device can be modified. Thus, it is possible to have a rapid-responding memory in the "auto" control loop with the improved resolution of a slow-responding system of "manual" control.

Pulse Interfaces

The output signals from the pulse controller can be used directly to drive the solid-state memory or certain types of actuator, but more frequently it is necessary to convert these pulses to another form. A stepping motor is often employed, and the interface device for this consists of a pair of gates which generate 24 volt a.c. signals whenever a d.c. pulse is present at the corresponding input. The resultant bursts of a.c. can drive the stepping motor directly. If a higher level signal is required, another form of interface must be used.

Auxiliary Equipment

In addition to controllers, electronic systems require several other functional devices: square-root extractors, multipliers, dividers, amplifiers, differentiators, integrators, limiters, selectors, fixed and adjustable bias units and so on. Frequently requirements arise for special functions which cannot be performed by a standard device, and in this case it may be necessary to develop special equipment. When this is done, however, the cost may be out of all proportion to the function, since small-volume production tends to be expensive, and since it is necessary to produce special assembly and functional drawings, test procedures and descriptions, so that spares can be provided and the equipment maintained over the economic life of the capital plant.

Mechanical and Electrical Design Aspects

From the preceding sections, it will be apparent that the form of the control equipment should be such that maximum flexibility of system design is afforded.

The equipment is based on a modular plug-in concept which enables any system, large or small, to be built up from a fundamental "library" of some sixteen basic modules. The modules slide into shelves, with plug-and-socket connexions being made to inter-module wiring on the back-plate of the shelf. The system variations are developed by suitable choice of modules, and by the inter-connexions between them. Special coding devices prevent any module from being inserted in the wrong location. During the early design phases of a project, sufficient spare spaces are allowed to enable the systems to be modified or extended at a later date.

It is necessary to take precautions against unauthorized tampering with control devices, since considerable damage could be caused to the plant by mal-operation of the control systems. Once the system has been assembled, the modules can be locked into place. Further security is gained by the provision of individual locking facilities on all adjustments—while the cabinets themselves are provided with lockable doors.

On individual modules, all components are permanently identified, and ample space is allowed in order to enable quick and easy repairs to be carried out.

Power supplies warrant special consideration. The systems must obviously fail safe if a loss of power occurs. For this reason, modules are not fused individually—since failure of a module fuse could cause faulty information to be fed into an otherwise functional control loop with, possible, disastrous results. Thus, all the modules serving a single loop are fed via a single fuse. Failure of this fuse, therefore, deprives all the modules of power and thereby locks out the loop. A separately-fused source is provided for manual operation. Of course, in spite of these precautions, if the *primary source* of power fails, even remote manual control will be impossible unless some stand-by power source is available. This is, of course, usually provided by one or two emergency diesel generators, which are arranged to start automatically on failure of the turbo alternator and to connect directly onto the bus bars. The control equipment must take its power from this source. There is a case for providing the control equipment with electrical power even in the event of total power failure; this can be achieved using static inverters operating from self-contained batteries which are trickle-charged while the main supply is healthy. This arrangement can only supply power for a short period, since the capacity of the batteries is fairly small, but nevertheless it can provide the engineers with important instrumentation and the ability to position the actuators for start-up conditions. This minimizes start-up time on restoration of a healthy mains supply.

Generally, on marine plant, fail-safe requirements dictate that on loss of power all actuators maintain the position held immediately prior to the failure. If, however, special requirements necessitate that an actuator takes up a pre-determined position on power failure, this can be arranged, but some source of emergency power for the actuator will then be necessary. This could be a hydraulic system with a pressurized reservoir, or it could be a pneumatic system with receivers to store the compressed air.

SYSTEMS ENGINEERING

The term "Systems Engineering" in this context covers the fundamental design of the control systems, the detailed engineering, the functional testing, and the optimization.

Computer Simulation

As more detailed knowledge on boilers has been built up, it has been possible to carry out increasingly accurate simulation exercises to assist in the design of control systems(2). Nevertheless, the dynamics of a marine boiler can seldom be predicted in total, and approximations are often made. The situation is, however, complicated by the fact that marine plant, although built to a basic design, is often built for different powers, with different manufacturers and peripherals. This does not enable the experience of one installation to be used in the design of succeeding systems.

Early approaches to simulation used analogue computers and linearized small-perturbation models of the most important sections of the boiler. Perturbations were generally limited to ±10%, or less, about a given steady-state condition, and, in order to evaluate system performance over a wide range of loads, the model co-efficients were calculated at several different loads. At this early stage it was realized that the severe interactions through the plant and its associated systems made it difficult to identify a single criterion which would be adequate for tuning all the loops. One criterion which was used was the Integral of the Absolute Error (ψ).

$$\psi = \int_{o}^{T} | \Sigma | \, dt$$

Since this expression defines the total area by which the actual response curve differs from the idealized step response, it will obviously reach a minimum at a particular controller gain, and this was selected as the optimum response.

Figure 17 shows how this criterion is optimized for a two-term controller, and from this it will be apparent that the curve gives a useful indication of the system response with various controller settings. In some cases the Integral of the

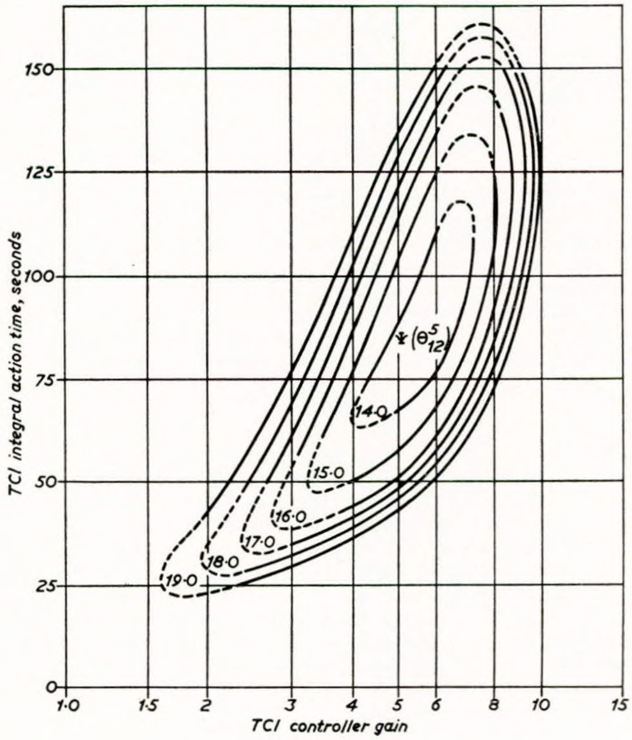

FIG. 17—*Optimizing criterion contours for steam temperature controller*

Absolute Error, plotted against controller settings, gives a very shallow curve, and it is then necessary to augment this criterion with another. One other criterion which could be used in such cases is the minimizing of the initial peak deviation.

The early studies showed the value of varying controller settings according to the boiler load, as this gave optimum control over a wider range of loads. They also showed that poor tuning of any one control loop could seriously impair the overall boiler control performance, but they also showed that better modelling techniques were necessary if greater accuracy was required, or if the response of larger load changes was needed. For this reason, later simulations have been carried out on larger, more versatile Hybrid computers, and serious attempts have been made to increase the accuracy of the model.

Early simulations were hampered by being treated as academic adjuncts to the main problems of marine power plant engineering. They, therefore, commenced at a late stage in the design and rarely were applied to specific plant with sufficient confidence to have much influence in the design or specification of the control system.

If it is desired to obtain an accurate model of the boiler this decision must be made at an early stage, and the importance of the programme impressed on all personnel. This has a great effect on the accuracy and therefore, on the relevance and value of the final result.

A further point which must be considered is that the control equipment manufacturer himself cannot be expected to provide all the data on the loop. His equipment forms, at best, only half of each loop. He can generally provide the transfer functions of his own equipment quite easily—this equipment is manufactured on a fairly large scale, and has fairly uniform characteristics from one device of a particular kind to another of the same kind. The remaining data on the plant is not obtained quite so easily for the reasons given.

Although most control equipment manufacturers will undertake to carry out simulation work, it is important that the main plant manufacturer provide them with all the necessary data.

Hybrid computers have enabled recent simulations to take into account the non-linearities of the boiler. This, too, has increased the accuracy of the results obtained—particularly for large perturbations.

The value of such simulations is not only that the design of the control systems is assisted by them, but also that useful data can be provided to commissioning personnel in order to assist them in tuning the control loops. It is also feasible that once the model is complete, the commissioning personnel can be trained on it prior to commencing work on the actual plant. It is for this reason that some models have used the actual control hardware to represent the relevant sections of the control loop, rather than modelling of these systems using the computer itself. This gives a more realistic impression to commissioning personnel, and also eliminates one possible source of error from the simulation.

Safety Considerations

The list of design requirements given at the beginning of "Equipment Design" included one stating that no failure may give rise to unsafe conditions. In the control loops of a VLCC Turbine Boiler Unit, the number of modules involved in the instrumentation and control may amount to some 50 or 60. Even if this criterion were to be applied only to the automatic control systems as such and ignored indication only loops, it would be obviously extremely difficult to meet. It is, therefore, common to divide failure modes into categories depending upon the effect of the failure on the plant, and also to consider the probabilities of any given failure.

Statistical information on failures of electronic devices is obtainable from several sources, and this can be compared with data obtained from the manufacturer's own experience. Current figures for components in modules indicate a mean failure rate of one per 40 modules per year. By the use of plug-in modules and monitoring techniques, the Mean Time to Repair should not exceed 0·5 hrs. (Of course, to meet this figure, it is essential that there are qualified maintenance personnel who are familiar with the equipment, and that suitable replacement modules are available immediately the fault occurs.) When these figures are combined, a predicted outage of approximately 0·0057% per faulty module is obtained. This figure does not take into account mechanical failures, on which statistical information is sparse, but if a pessimistic view is taken and a factor of ten allowed to compensate for this aspect, a system of 140 modules will have an availability of 99·9%. In spite of the High Mean Time Between Failures indicated by these figures, it is necessary to build into the system designs certain safeguards which further reduce the possibility of a dangerous condition being generated by a failure. The arrangement shown in Fig. 2 for an oil-fired boiler includes maximum and minimum selectors which provide a significant improvement in the safety aspects, since failures of any components can be shown to give rise to a safe condition. By using the fusing concepts described earlier, together with the standby power supplies described there, it is possible to obtain systems which have a very large safety factor.

Commissioning and Optimization

The process of commissioning a control system (as distinct from commissioning the individual pieces of equipment of which it is comprised) generally involves the injection of disturbances into the loop, and the observation of the result. Possibly the best known procedure for tuning a controller to a process is based on work carried out by Ziegler and Nichols(3), and involves applying a step in the signal to the actuator whilst the loop is on manual control. Other techniques are described in several works(4,5) but all involve similar disturbances.

On marine plant the actual time allowed in the ship's trials programme for tuning control systems is very short, and frequently ships complete trials with only adequate controller setting rather than optimum. Even this is only achieved by the use of multi-channel recorders which are used to monitor plant and control system parameters, and controller proportional bands and integral terms adjusted by empirical methods. Further, to obtain these empirical controller settings it is necessary to have plant load changes over the complete operating range until satisfactory results are obtained.

For these reasons, attention has been increasingly diverted to tuning methods which do not involve disturbances to operating plant. Correlation methods are an obvious possibility, and their use has been described elsewhere(6,7). These techniques enable the plant characteristics to be quickly identified, and hence the control systems to be tuned without significantly affecting normal plant operation—even in the presence of considerable plant noise. However, because of the cost of the equipment necessary to perform this type of optimization, compared with the benefits, this technique is not at present used on marine power plant.

Naturally-occurring noise was at one time proposed as a method of obtaining plant characteristics, but this technique has not been developed to the stage where it has been applied to marine power plant of this nature.

DIGITAL COMPUTER APPLICATIONS

Digitally-Directed Analogue Control

The simplest approach to on-line computer control is to have analogue devices performing the modulating control, and to use the computer for start-up and shut-down purposes. This process is known as digitally-directed analogue control (DDAC), and it also sometimes involves the adjustment of controller set points by the computer to optimize system performance.

DDAC systems are aided by the use of analogue pulse-output controllers, as described previously, since the analogue loops may then be switched on and off-line by simple contact-closure signals without the necessity of carrying out any balancing operations. A computer can start up the plant by operating directly on the actuators via simple contact-closure signals: it is unnecessary to generate analogue position-demand signals.

If manipulation of set point signals is required, it may be necessary to generate analogue signals, although contact-closures can be used to drive either motorized potentiometers or solid-state memories.

This type of arrangement is necessarily expensive, since the analogue controller and the computer act in parallel and there is, therefore, considerable redundancy in this approach. Nevertheless, the reliability of the system is high, and this consideration can justify the increased cost.

Direct Digital Control

Where the computer operates directly on a plant for control purposes without the provision of analogue controllers, the system is known as "Direct Digital Control" (DDC).

In principle, the control systems are essentially the same as described earlier but the possibilities of applying sampled-data(8) and other modern control techniques, when a computer is used, facilitates the provision of control systems which are perhaps better able to handle some problems than the analogue equivalents. In particular, the very long time constants in the superheater system, which normally necessitate the use of cascade control, can be better handled by a sampled-data system. It is also possible to develop control algorithms which include limiting or selective constraints—which greatly facilitate the integration of start-up with modulating control systems. One such technique(9) includes derivative-limiting and "integral wind-up" limiting systems. These had a beneficial effect on the control loops, which was attractive for the process under consideration.

The interface equipment is again similar to that used for an analogue system, and it is still a requirement to provide manual back-up facilities, and to consider the effects of power-supply failure. With the advent of the Minicomputer, it became possible to propose fairly comprehensive control systems in which the cost of the computation device was very much lower than the cost of the equivalent analogue system. The advent of the microprocessor has improved the economics of DDC even further, and has the added advantage that it is feasible to consider fitting *several* microprocessors on a given ship—each being dedicated to a particular task. This considerably improves the reliability since all the eggs are not then in one basket.

A few well-publicized examples of a central processor being used for many varied functions on board ship (including main engine control) exist(10), but in the authors' opinion this concept (with costs as they are and with the requirement of analogue back-up loops to guard against the event of computer failure) is not likely to gain much ground in the near future.

The most likely development is the use of microprocessors for direct digital control of individual systems. At present it appears that this solution will soon be available at a price to compete with conventional analogue control. The next development may then well be those local digital controllers being connected to a central computer which would collect data and "manage" these local controllers adjusting set points and perhaps altering controller characteristics.

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Discussion and Authors' Replies

MR. R. B. ALLEN, F.I.Mar.E., in opening the discussion, said as a presentation of the merits of electronic control and in particular the pulse technique, he found the paper most interesting and refreshing. In some other aspects there appeared to have been little change over the past nine years. Regarding the system diagrams he was a little puzzled by the comparator before the controller. Was that actually a separate instrument, or was it the input circuit accommodated within the controller? Referring to the level control (Fig. 9) that indicated that any difference in steam and water flow would modify the deviation signal, but the description suggested that it would modify the set point; it was true the final result was the same. Could the authors clarify that point?

In the combustion control system there was reference to automatic burner operation based on boiler load during manoeuvring. Was that used, or were burners operated by remote manual methods based on the judgement of the engineer in the control room? Could the authors comment on the method currently favoured?

With regard to the bridge control scheme, which unfortunately was not shown in full, did the authors' company produce a system which was linked to the combustion control so that the rate of manoeuvring might be modified to match the boiler condition? There was a reference in the paper that "the control loop responses must not only consider the particular controlled parameter, but the effect on all other systems". The authors' views on that point would be much appreciated, although there had been some reference made in the presentation of the paper by Mr. Machell. The speaker wholeheartedly endorsed the authors' views on the problems of commissioning control equipment in ships. That insufficient time was allowed for optimum tuning and possible modifications during trials was a very old problem still very much with them, and he was surprised that impartial bodies such as the classification societies did not show more concern that it was done properly, thoroughly proved during manoeuvring, and the final settings recorded in detail.

There was undoubtedly a difference between the specialist skills desired or presumed to be on board and those actually available. The authors quoted a mean time repair of half an hour or less, but to meet that figure it was essential that there were qualified maintenance personnel on board who were familiar with the equipment. It might not always be appreciated that marine engineers were not specialists in control engineering and electronics, and that their studies and examination requirements in these subjects were limited, as also was their test equipment.

Personally, he would like to see a new approach by some control equipment manufacturers to give more consideration to the style of technical literature produced for a ship with the emphasis on useful information on the system before the instrument.

A full set of typical signal values between each instrument in the system, when on full power, might do more to assist in the location of a fault than a lot of detailed information for repairing an individual instrument which could not be located.

Of course that returned to the problem of thorough tuning of the system initially before the information could be provided, and in that respect it was no reflection on the control engineer, who was seldom afforded anywhere near the time required during trials, as previously stated.

Since the authors' company manufactured both pneumatic and electronic systems, could the authors give an indication of a cost comparison between the two systems with a standby battery arrangement? Would it not be feasible to limit the latter to supply the hand/auto stations only for remote manual operation, thereby reducing the size and cost of the emergency service? Finally, the speaker wondered if the authors could give some information on the electronic actuators, as these were not illustrated in the paper.

MR. MACHELL in response said that Mr. Allen was correct in stating that the comparator shown before the controller on the systems diagrams was in fact the input circuit accommodated within the controller. The second point asked for clarification on the specific arrangement of signals in the three-element feedwater controls. The end result was the same; the steam flow/feed flow deviation was added to the set point signal and the resultant compared with the measured level in the input network of the level controller. Therefore, the particular hardware configuration meant that steam flow/feed flow deviation modified the drum level set point signal.

There are three methods of achieving stable combustion control under manoeuvring conditions, which for most ships sailing with unattended engine rooms did not allow for remote manual control of the burners. The first and most obvious solution was to have burners capable of achieving the required turndown, but frequently alternative solutions had to be considered and the two most often employed were to sequence burners automatically, or to operate a steam dump valve.

Fig. 19 showed a combustion control system including automatic burner sequencing. The particular points to be noted are, firstly, the importance of consultation and interfacing with the burner management system. The air flow signal as taken from a measurement of register draught loss must be compensated for the number of burners in operation, as the air flow was compared with total fuel flow. The signal to sequence burners was taken from a measurement of fuel oil pressure.

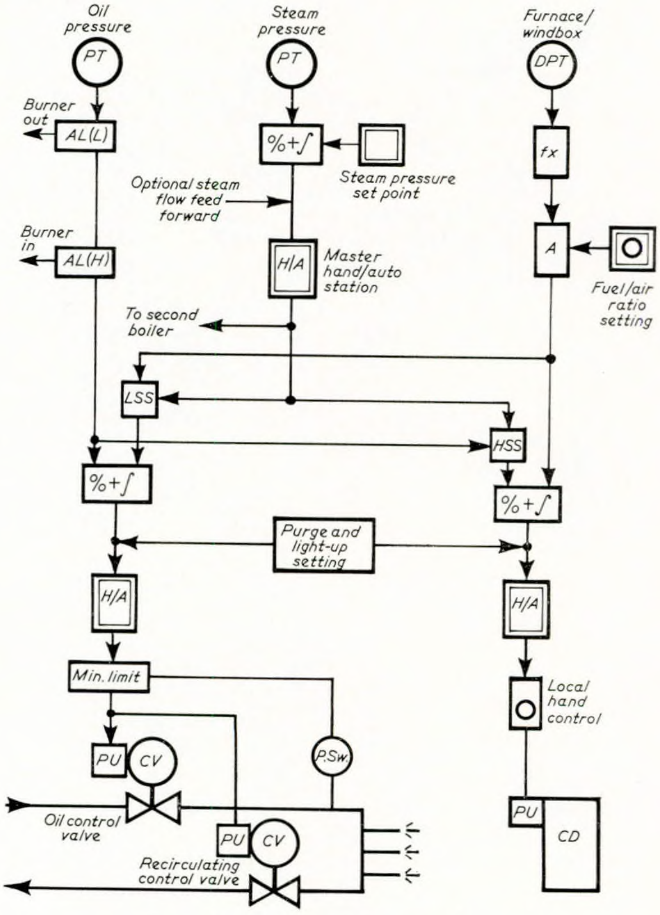

FIG. 19—*Combustion controls*

In presenting the paper the authors had illustrated a more complex block diagram for a manoeuvring system (Fig. 20).

This included limiting circuits from the boiler control systems. The authors believed that each system must be tuned with effect on other interactive systems in mind. For example, the turbine rate of change must be limited to enable the boiler to follow. This reasoning applied to many other engine-room control loops, and it was only by attention to all connected control systems that the engine room would operate at optimum.

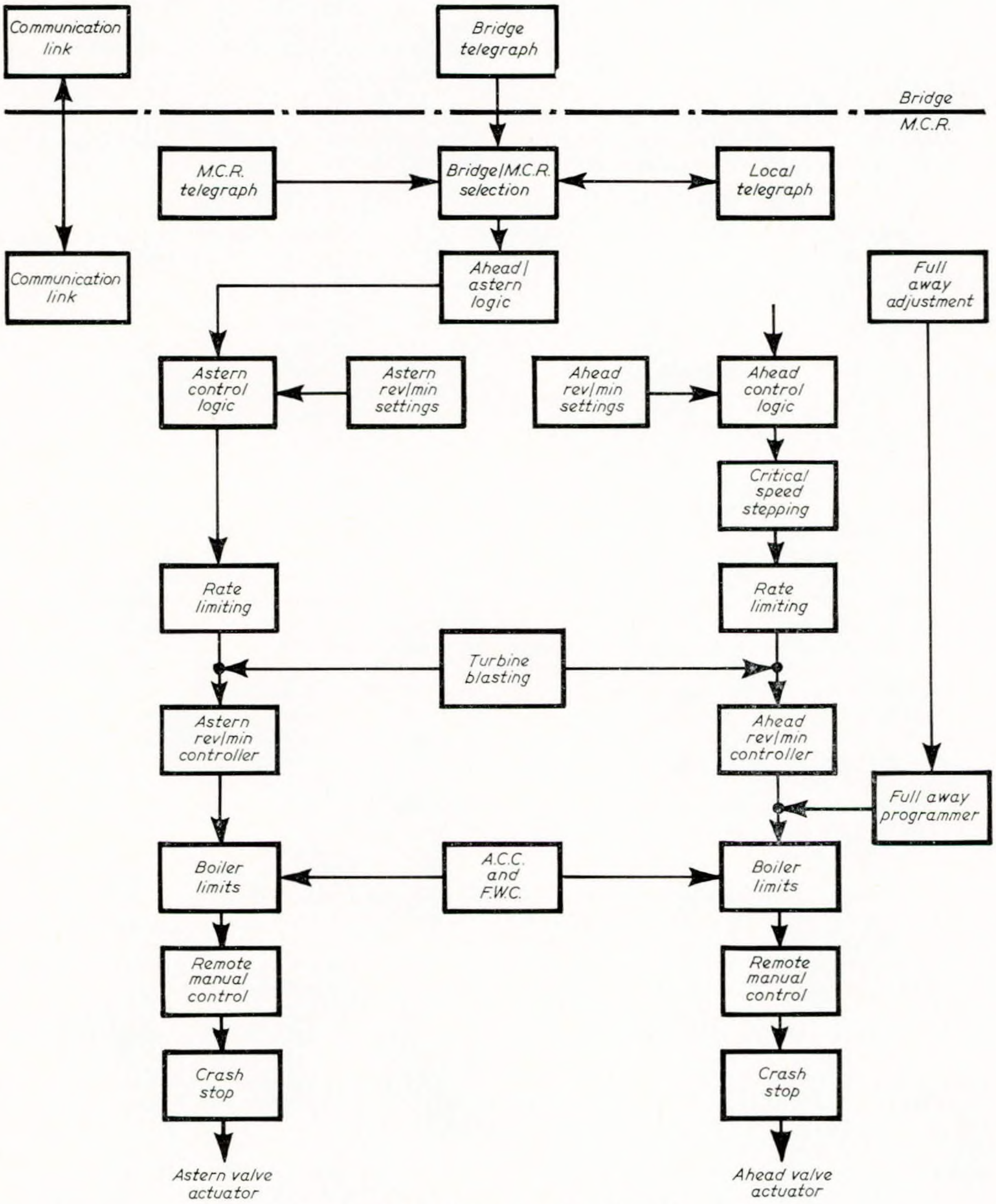

FIG. 20—*Turbine controls schematic*

Mr. Allen's point on commissioning, staffing, and literature were noted with interest.

The authors estimated that on a purely hardware cost (i.e. not taking into account installation) pneumatic systems were some 15 per cent lower in cost than electronic systems, but the authors believed that when all factors were considered there was very little difference in final costs.

It was not feasible to limit the standby battery arrangement to supplying the hand/auto stations only, as the engineer had still be able to see the plant condition. This probably meant at least including transmitters to be connected to the emergency supply. The control system fusing philosophy adopted by the authors' company entailed that the control equipment was also fed from the same fuse as the transmitter. With this in mind it would be difficult to reduce the size of the emergency power supply arrangement.

There were several types and manufacturers of electrical actuators, which would interface with the control equipment described in the paper, but all these actuators tended to be expensive without offering any significant compensation factors (such as improved performance) to justify the higher cost.

MR. R. YOUNG asked why there were two monitor modules in one of the cabinets.

MR. MACHELL replied that this was because of the distribution of modules. Each module had capacity to monitor up to 24 signals, and during the engineering of this particular job it was decided that in this cabinet more than 24 signals required monitoring, hence the need for the second monitor module.

Mr. N. M. Pope asked whether the operator would know which monitor would apply to which piece of machinery.

Mr. Machell replied that that would be identified on the cabinet door; a label identified every point on the monitor module, by module type and position in the equipment cabinet.

Mr. Pope asked what information was supplied.

Mr. Machell replied that the information indicated the value of the analogue signal, for one set of conditions. This was normally for full away with all control systems and plant operating correctly.

Mr. Machell said that was within the equipment cabinets. It was a maintenance and fault finding procedure rather than an operation feature. The operator at the control desk was presented with all the necessary information to enable him to operate the plant in a safe and efficient manner.

Mr. Pope felt that if one was fault finding it would be a lot easier if one knew what the settings were when the gear was running properly.

Mr. Machell replied that identifying or quantifying the analogue signals was only feasible for one set of conditions. It would be a useful advantage to ships' engineers if that set of conditions could be identified: this could be with a full-away condition with all burners working and all plant in a known condition. The difficulty was that when one was trouble shooting it was because of some plant or equipment fault and under these conditions it was extremely unlikely that the plant would be running at the conditions under which the initial measurements had been recorded. Typically, the oil demand for pressure on a sub-loop could vary from 1mA to 9mA. It would be very difficult to identify the value for every signal in a system for a number of set conditions. It was an understanding of the system which could make it apparent that there was an obvious component fault. In the author's opinion fault finding on electronic systems described in the paper, with the modular approach and monitoring facilities are simpler than with pneumatic control systems.

Mr. Allen said that the author had suggested that it was difficult to provide any information because at the time of trouble one did not get suitable signals. Several references had been made to the basic understanding of the system, but surely there were areas where engineers might not be able to say whether signals were expected to be high or low, such as where an instrument was reverse acting or biased.

Mr. Machell replied that the recognized procedure was for the engineer on board to leave a set of drawings marked up with analogue signal values and controller settings so that known conditions were recorded. That was not only useful for the ship's engineers but for the service engineers if called to the ship. The control system drawings and descriptions would make it clear as to obvious signal manipulations such as signal reversals, high and low limits, and bias signals.

Mr. Allen felt that often that was not done. He sympathized with the authors that control equipment suppliers were not given the time to deal with such matters, and that the shipowners seemed to be more interested in getting the ship into operation. The speaker was surprised that owners did not take more interest to see that more time was given to such matters.

Mr. Pope referred to old fashioned pneumatic equipment, and said one could see at a glance what was happening.

Mr. Lindsley replied that the monitor module was shared round several loops, and one had to turn a switch to make it read different signals. If people wanted to buy one meter for every module that would be actively encouraged. But the author questioned how many pressure gauges were used with pneumatic systems. Frequently, gauges were fitted to air pressure supply lines. The authors' company provided test facilities in a pneumatic system for measuring the pressures at the input and output of controllers: rarely did they have a fixed pressure gauge in those positions. Of course, there were gauges on the panel for displaying the controlled parameters. Those were the signals one needed when operating.

Mr. Machell felt that electronic systems should repeat the information available with pneumatic systems, and this in fact was the case with regard to information available on the operator's panel.

Mr. Young pointed out that the chief engineer was more concerned with the plant than learning how the equipment worked at that time.

Mr. F. Nash wondered whether it was possible to build and supply ships with a system which would plug into external equipment interface connexions so that when a ship was in port the engineer could take the control system through its full performance. Would such equipment be too expensive?

Mr. Lindsley replied that it would be possible. Regarding it being expensive, that was a relative term. One had to weigh up what it was going to save in the long term. If it was going to make a significant saving, then it was worth spending the money. There were simulated systems which were applied, but any simulation system tended to check the control electronics. For example, in one system an artificial signal was fed into the control loop and the device checked that the output signals were right. However, this process left out the least reliable part of the control system: the transmitters and actuators. The electronic equipment they had had proved reliable, but faults had been in the mechanical linkages, actuators and transmitters. Those were the difficult things in any system. Most of the simulators spent their time checking the most reliable part of the system, while the least reliable part was not checked.

Mr. Nash commented that obviously checking transmitters was a necessary commitment on all control systems, and asked if there was not a recognized method of doing this?

Mr. Lindsley replied that one would need to supply a pressure transmitter with a pressure in order to check that it was really working: that was the only way to see that a transmitter was really doing its job.

Mr. Nash suggested that if transmitters were fitted with gauges on both impulse and control slides any malfunction would immediately be apparent.

Mr. Lindsley replied that probably would be so. Systems of that type were fitted. If one wanted to impose a test on a transmitter one had to have a means of generating some pressure. That tended to be rather expensive compared with a simulator to check the control electronics. The simulator could be simple.

Commander M. Usher, F.I.Mar.E., referred to actuators. One important aspect not dealt with in the paper concerned the actuators operated by the control system. To obtain the maximum advantage from the electronic form of control, the actuator here, and some form of pneumatic device was still popular although the electro-magnetic transducer was not entirely satisfactory. There appeared to be a need for an improved electrical actuator for such applications. Would the authors like to comment on this topic?

MR. MACHELL replied that the state of the art at the moment was that it was a commercial decision: electro-hydraulic actuators were adequate but expensive, pneumatic actuators were adequate and cheap. Electric actuators still needed some work to be done on them. The electric actuator did not have the speed of response nor the discrimination of the pneumatic or hydraulic actuator. That was the situation as they saw it at the moment.

MR. LINDSLEY said the authors' company was investigating small electric actuators—these tended to be at the small end of the range and had, to date, been rather slow.

An electric actuator was a motor driving through a gearbox or output shaft. The motor was essentially a high speed device and the gearbox was used for speed reduction. A lot of problems came in there: if one wanted good resolution and high speed, one had to get the motor started, running and stopped very quickly indeed. That was one of the main problems.

Electro-hydraulic actuators were expensive but their performance was generally satisfactory, and for heavy inertial loads they were preferred to pneumatic actuators.

One of the problems was costing the exercise. People thought of a pneumatic actuator as being a cheap device since the compressor was costed as a separate entity because it was needed for other purposes. The electro-hydraulic actuator came with its own built-in pump and power supply, and this was quite a good approach technically, but commercially it militated against electro-hydraulic actuators.

Of course, in the long term, the authors would liked to have seen more completely electronic systems. There would be a better reliability inherent in such an arrangement and no doubt it would come in time.

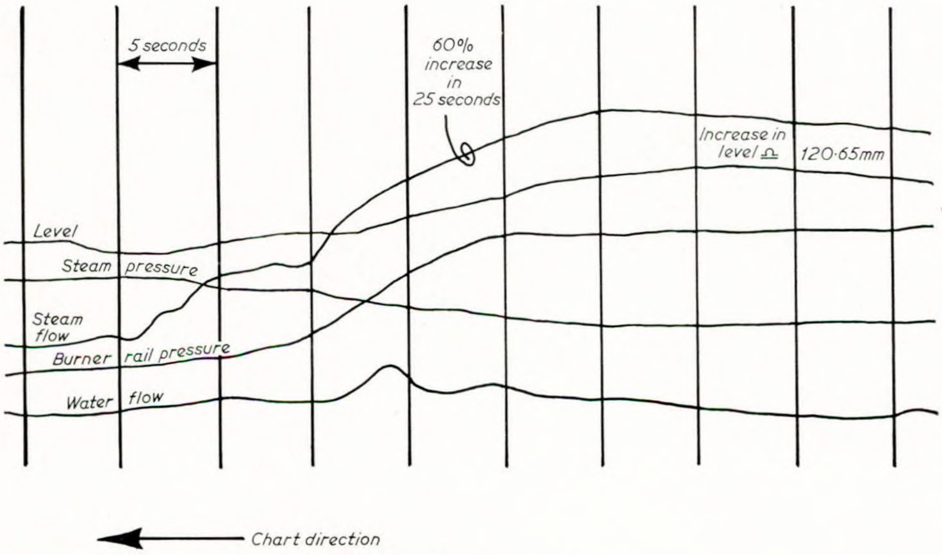

FIG. 21—*UV recording ship trial*

MR. R. J. HUNT, M.I.Mar.E., noted with interest a diagram presented during the lecture showing a boiler load change of 60 per cent in 25 seconds. The authors were asked of experience regarding system performance in terms of control response and if they considered the load change shown on the diagram typical: would the authors have expected the boiler steam pressure to be maintained at a constant value by the control system under such conditions? Referring to the industrial package type boiler, in many ways similar to the marine boiler, but operating with rapidly fluctuating loads and needing close control of steam pressure—what was the authors' comments on use of electronic *versus* pneumatic systems for such installations and to what extent is control system response determined by choice and specification of actuators? Referring to the more detailed logic diagram showing interrelationship of main control loops and anticipatary loops, could the authors comment on the use of a steam flow anticipatary device linked to fuel flow as a means of controlling the final steam pressure under rapidly fluctuating loads? Finally, could the diagram referred to earlier showing load changes and the more detailed logic diagram be reproduced in the reply.

MR. MACHELL replied that Fig. 21 was a tracing of a u.v. recording taken during the sea trials of a VLCC. This was typical of traces taken during trials, and for a marine boiler, a typical load change. The response of the boiler parameters, such as steam pressure, steam temperature and drum level, for a typical load change were very difficult to predict, since so much depended on the boiler dynamics.

The results show in Fig. 21 could be considered typical for drum level control with an increase in level of approximately 120mm. The reduction in steam pressure of about 10 per cent was, perhaps, slightly more than could be expected with control systems optimized.

The authors believed that for marine boilers as well as industrial package boilers, control system performance did not normally depend on whether electronic or pneumatic control systems were fitted but more on correct system design.

Similarly, with the moderate actuator power required to operate valves and dampers on marine and packaged boiler systems, pneumatic or electro-hydraulic actuators were both satisfactory. It was only when very high inertia loads were operated that electro-hydraulic actuators became necessary.

There were several types of electrical actuators that could be considered for use on the size of plant being considered, but care must be taken in selecting an actuator with sufficient power at the rates of movement required, and that there was no limitation on frequency of operation and resolution.

Fig. 19, the combustion control system referred to in answering Mr. Allen, includes a steam flow feed forward signal into the boiler pressure control system, and was frequently employed where the plant was expected to operate with fairly large and rapid load changes, There was no doubt in the authors' minds that better overall response could be achieved.

MR. HUNT said the boilers to which he referred were generally described as of the "package" nature, and were not equivalent to marine boilers. Runs with pneumatic boiler controls appeared to be longer. He was interested to know what the authors considered to be long in terms of pneumatic piping runs.

MR. MACHELL replied that with package boilers the length of run was not usually significant. Pneumatic signal runs of up to 61 m (200 ft) should for most control systems be acceptable; runs of up to 122m (400 ft) could also be satisfactory, provided that the controlled parameter was not too sensitive. The authors recommended that for runs above 61m (200 ft) each case must be considered in detail, but they had experience of systems operating quite satisfactorily with these long transmission distances.

MR. NASH referred to steam temperature control. The authors had talked about cascade control, and the speaker asked for further information.

MR. MACHELL replied that a typical electronic cascade steam temperature control system was shown in Fig. 22.

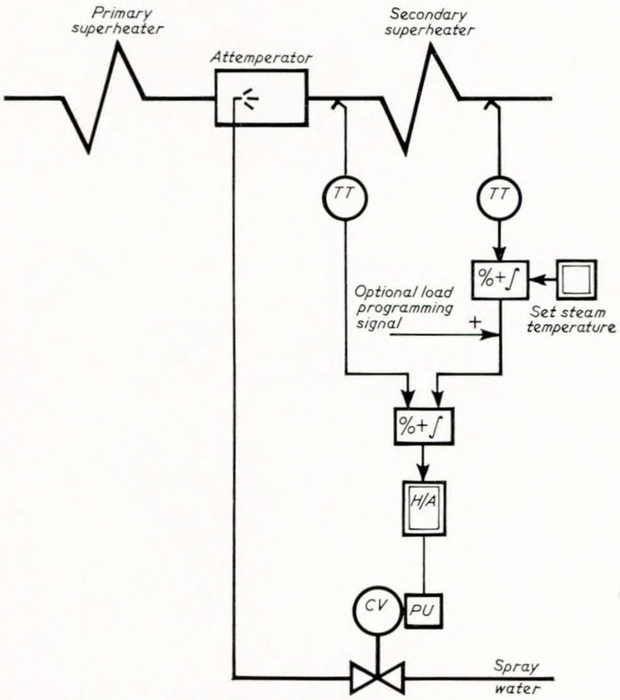

FIG. 22—*Steam temperature control system (cascade with load programming)*

The steam temperature was measured after the attemperator and before the final superheater section, and was maintained as a desired value set by the output of steam temperature controller C1.

The cascade controller C2 corrected the spray valve position to maintain the steam temperature after the attemperator at the desired value (which is set so that the final steam temperature was correct).

Plant disturbances which caused a change in steam temperature entering the attemperator was measured with virtually no delay by the attemperator outlet thermocouple, and compensated for by re-positioning the spray water valve, thus avoiding the relatively long time delay of the final superheater.

Further disturbances in the spray water flow, which may be due to feed pumps or drum level control systems, are quickly recognized and corrected.

MR. K. V. VARMA asked whether, in the electronic control system components on board ships, there was any way of knowing which component was deteriorating before it actually broke down, so that a replacement could be effected in time? For example, a component such as the amplifier shown by the authors, even though its gain reduced drastically (possibly due to age), might not make much difference to the output until it broke down totally, which was a serious thing to happen at sea. Also could the authors say how the various components would be affected by vibration?

MR. LINDSLEY replied that they did not find aging effects on the control equipment quite as often as one might have expected. Aging occurred generally where modules had gone through some kind of soak test to make sure that the first part of the aging characteristic was taken out. Aging tended to be largest during the initial running in (which since it was carried out in the factory before shipment, did not affect the performance of the installed system), and then it flattened out. Regarding the amplifier, they found that it would continue to function well and if it went wrong the effects were generally that the gain would change drastically.

Vibration probably affected things like potentiometers, where they had to be very careful in meeting test requirements regarding vibration, vibration did not affect the static characteristics of a transistor or anythings like that. It could perhaps have caused a capacitor to physically fall off, but no effect on the electronics was known to them at the moment.

COMMANDER USHER referred to microsystems and to tuning. In the paper the authors had referred to micropressors for direct digital control which improved the economics of such an operation. The difficulty of allowing adequate time for tuning in some shipyards had already been referred to. Did not the introduction of this type of control make the problem of correct tuning more difficult unless there was a full realization by both shipyards and shipowners of the importance of this task?

MR. LINDSLEY replied that the danger had now passed of having some "mad computer engineer" put in a system which only he understood, and on which only he could change the parameters. People realized that systems had to be understood by ordinary human beings, on a ship working under rather difficult conditions, and that changing things like proportional bands should not need a six months' course in computer programming. Those dangers were no longer with them, although at one time they seemed to be heading their way. With modern computer control systems, even those using minicomputers were designed so that in ordinary, plain language one could ask the computer to put a different proportional band on a control loop. Apart from the fact one might type an instruction rather than turn a knob, the whole things was very similar to a conventional system. The same techniques should be applied to microprocessor systems. It should be easy to change characteristics. They had already talked about hunting or instability; the range of proportional bands one had to put on a controller to cope with the possible functions was enormous —ranged from 2 per cent to 1000 per cent. The microprocessor had to be capable of doing the same thing if it was going to be used on the same basic plant. One had the same problem with which to cope, so it had to do the same job, even though the processing side was more difficult and complex.

COMMANDER USHER felt that there was difficulty in setting proper tuning and he referred to a complication which might not have a direct advantage in terms of operating the plant. There always had to be some compromise between what might theoretically be the best control arrangement, with, for instance, derivative limiting and integral wind-up limiting systems, and the remitting complications in properly tuning the system and maintaining performance. What for instance, was likely to be the real gain in plant operation economics with such systems in practice?

MR. LINDSLEY said that in a boiler there were a certain number of parameters that one could measure and a certain number one could adjust. One could measure steam temperature, pressure, oil flow, air flow, and one could make certain adjustments. If one looked at those essentials, the input to the system, and the outputs from the system, those were the common factors. One could have a pneumatic system, an analogue electronic system or a computer in between. Essentially one was twiddling the only knobs one had to twiddle. If one could get those things working well; if one could control the oil to do what the man sitting looking at the boiler decided he wanted to do, once one had that—and that was not as easy as it sounded—putting a control system in was only a little more complicated. One almost got the control system for nothing. It sounded a simplification but the speaker was merely repeating something put to him by a client. Once he had got over his problems with actuators, he found his control systems worked well. That was true of the microprocessor. Once the actuator was working reliably, and once there were accurate measurements to which the human being could respond, there was no trouble in the system working well.

COMMANDER USHER said that one of the difficulties with ship control systems was that they were often forced to match differing plant characteristics which were often unknown during the system design stages. There would clearly be a great advantage in standardization of ships' plant performance and this might make the economic justification for simulation rather greater.

MR. LINDSLEY replied that they would like to see more series building. Once equipment were turned out at the rate like BAC 1-11s, the control system design was simpler. One could do an analogue simulation before one started and justify the cost of that on several indentical installations. It was not so easy to do that if every installation one did was different from the previous one. One was then forced into the situation where a commissioning engineer was sitting with 300 other people in a ship designed for 30 people trying to make a brand new system work, knowing there would never be another system built like it again. That was a very sad situation which the industry had been forced to in the past, but which series building could alleviate.

MR. D. R. SUMMERSON referred to actuators. He wondered what would happen if the air supply to the actuator failed?

MR. LINDSLEY replied that there were several options available. One was an air failure brake which, if the air supply failed, locked the shaft (it was a mechanical brake).

MR. SUMMERSON felt there might be a requirement for the actuator to fail in the open or closed position.

MR. LINDSLEY replied that sometimes that was the requirement. Sometimes the control systems designer was asked to ensure that if the supply failed then the actuator would be arranged so that the valve was either shut or opened.

MR. YOUNG asked whether it was possible to obtain instruction on the system control.

MR. LINDSLEY said his firm carried out courses and they were of considerable interest. It was essential that one had the right type of person on board ship. People could go in for all sorts of courses but if they were not going to be any good in a crisis then a course was a waste of money. There were courses available in order that people could learn the principles of control and the logical approach needed to solve problems.

MR. YOUNG said that meant that after trials had taken place, there could be somebody still on board ship who could help to settle things down.

MR. LINDSLEY replied that that was so.

MR. A. W. DAVIS President, I.Mar.E., and Chairman of the meeting made the following points:

A number of the figures in the paper referred to a black box marked as follows:

$$\boxed{\% + \int}$$

but an explanation of the function of this unit was not given. Engineers might not want to know how this unit operated in detail but they were vitally interested in what the unit achieved and how it affected the system. How much information was included in the manufacturers' handbook and what level of testing was the seagoing engineer expected to be competent to carry out? The problem was where to draw the line between what the seagoing engineer must know and what he did not have to understand. At what technical level should the line be drawn?

Fig. 13 showed a pressure transmitter. Why did the layout allow so much space between components as the unit appeared unnecessarily large?

There appeared to be a contradiction in the paper where the authors said that the cost of the cable installation could be reduced by using the two wire concept in which the power for the transmitter was fed via the same wires that carried the signal information in the form of a current. Later, the authors said that since the power wires were best segregated from the signal wires to avoid possible interference problems, the cost of the cable installation was considerably increased.

Could the authors explain what they meant by the term "power failure". Was it a total blackout of the ship or just a failure of power to the control equipment? If the former the ship might be at risk from collision or grounding and was a much more serious situation than the latter.

In reply to Dr. A. W. Davis, THE AUTHORS said that the nomenclature given at the front of the preprints gave a factual definition of such symbols as $\% + \int$, which was a proportional plus integral controller. The authors believed that all marine engineers training should cover basic control theory, which would entail understanding the operation of such items as controllers. It was not necessary to understand how a particular unit worked, but the effect this should have in a system.

A seagoing engineer should be able to feed in a known signal into a unit, measure the output and determine if that unit was operating correctly. This could be done on the equipment described in the paper with electronic modules in the equipment rack and using the monitor module provided.

The transmitter shown in Fig. 13 was a development of a well proven pneumatic transmitter, and for commercial and technical reasons employed some common equipment. Its size was not usually an important consideration for marine applications.

With regard to the comments in the preprint on cable costs, it was intended to state that not only was a two wire transmitter more economical in cable than a conventional transmitter requiring five wires, two for signal transmission and three for power supplies, this was made more expensive because of the recommendation that power and signal wires were not run together, therefore a two-core and three-core cable were necessary, thus being that much more expensive.

Correspondence

Mr. R. G. Boddie, M.I.Mar.E., wrote that a few years ago, during sea trials on a newly built trawler, it was found that the main engines, when operating in automatic control, were stopped whenever the ship's radio transmitter was used due to radio interference. Could the authors please explain the steps taken to avoid the effect of interference and also how the use of signals in the 0-20mA range overcame this problem?

Written reply to Mr. Boddie

Certainly unless some care was devoted to preventing these problems, interference could have a serious effect on the operation of some electronic control systems. It need not be confined to radio interference. There were many sources of electrical interference on board ship with frequencies ranging from d.c. to several hundred MHz, Every solenoid valve, relay, motor, must be considered as a possible hazard.

It was impossible to completely suppress all of these devices although international legislation had been aimed at reducing the effects of interference from them. The only real solution was to have an electronic control system which by its design was immune to interference. Again is was not possible to achieve complete immunity but a very high level could be reached.

The 4-20mA signal range was just one example of a current transmission range and all these ranges were better from the point of view of rejecting interference when signals were transmitted by cable over any distance through areas of electrical interference. The true reasons for this immunity were complex but one could simplify the theory and think in terms of current flowing from the transmitter along one wire to the destination and back along another wire. If interference tried to force more current through this circuit the current must flow through the generator which would tend to react and compensate for the interference. With voltage systems, on the other hand, the generator was not aware of the voltage appearing at the destination has been increased due to interference. It therefore could not compensate. That, very simply, was why a current system wins over a voltage one in signal transmission.

The 4-20mA system as already stated was just one example of a current range. There are others such as 0-10mA, 0-20mA, 10-50mA, etc. Each of these has its own proponents but the effect remained that the live zero signal (i.e. one which was based on 0 as the starting point) enabled considerable economies to be effected since the transmitter could actually be powered from the same two wires that carried the signal information. Again the reasoning behind this was beyond the scope of the presented discussion. It was merely sufficient to state that the live zero ranges require only two wires for every transmitter. All other ranges require two or three additional wires carrying power to the transmitter.

The above had concentrated on signal transmission through areas of electrical interference. Once these signals had entered a cubicle or cabinet containing electronic equipment the arguments were not so important since the cabinet itself acted as a shield and precautions could be taken by the manufacturer to ensure satisfactory screening and filtering of incoming and outgoing wires. For this reason many systems employed voltage transmission within cabinets, particularly since this led to great economy.

Where reports of interference such as mentioned in the question had arisen, it was probably in installations where the equipment designers had encountered far more interference over a wider range of frequencies than they had anticipated. This risk was always present but by using equipment designed by companies who have a great deal of experience with shipboard electronic systems, the risk could be minimized. Certainly these companies would take precautions to ensure that their electronic equipment cabinets provided adequate shielding, and they would gladly advise on any special precautions which may be necessary regarding screening and earthing of cables. This latter point need not be as complex or as expensive as it sounded. Many systems were operating satisfactorily on modern ships with only simple screening of multi-core cables.

Mr. D. R. Summerson wrote that the discussion had seemed to reflect in some measure what he believed to be the wider lack of understanding of current automation and control practice being applied to the marine industry. This was understandable considering the rapid advances in marine automation demanded by the increasing number of ships with unmanned engine rooms and remote control systems.

His own company was currently producing documentation covering automatic control systems for the main propulsion and ancillary plant on a variety of ships for major fleet operators. This documentation was being aimed at providing ships' engineers with a basic understanding of particular control systems, followed by operating procedures for those systems. A further development could then be the provision of fault diagnosis aids. Control system documentation was also frequently provided as a back-up to a general machinery and plant operating manual.

Ships' engineers had found this form of documentation especially helpful because it provided concise and comprehensive information for complete control systems from one source document.