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Validation of the Type 23 propulsion plant design

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SYNOPSIS

Extensive shore testing of the Type 23 propulsion plant was undertaken because of the requirement of developing a viable electrical propulsion plant for the Type 23 Frigate within very stringent technical and operational parameters. The paper discusses the various types of shore trials undertaken and their influence on the design of related systems.

INTRODUCTION

In the Type 23 project the shipbuilder was required to take overall design responsibility for the project from the end of the design concept phase. It was a prime objective to reduce both procurement and through-life costs. The Type 23 is an anti-submarine frigate with added general purpose capability. This is an inherently expensive option but it is initially accepted that the design amounts to a competitive and cost-effective solution to the problem given that the ship can be expected to spend much of its working life in a general purpose role.

SYSTEM DESCRIPTION

Machinery fit

The basic machinery fit was conceived by MOD and has been engineered into a practical working arrangement (see Fig 1).

Gerard A McDougall has a BSc (Hons) degree in Electrical and Electronic Engineering. He joined YSL in July 1983 and embarked on a graduate training programme towards chartered status. He spent 2 years as a Senior Design Engineer within the Machinery Controls Department, the main responsibility of which was the overall Ship Simulation Database and the Machinery Control and Surveillance (MCAS) system. His last post was as a Senior Design Engineer in the Electrical Design Department with responsibility for the Type 23 Data Acquisition System.

He is also a participating member of the CAD/CAM Steering Group.

In 1986 he commenced a 3 year part-time MBA at Glasgow University.

Machinery requirements

The requirements for the machinery are:

1. prolonged low speed operation.
2. flexibility of operation.
3. high endurance capability.
4. low noise.

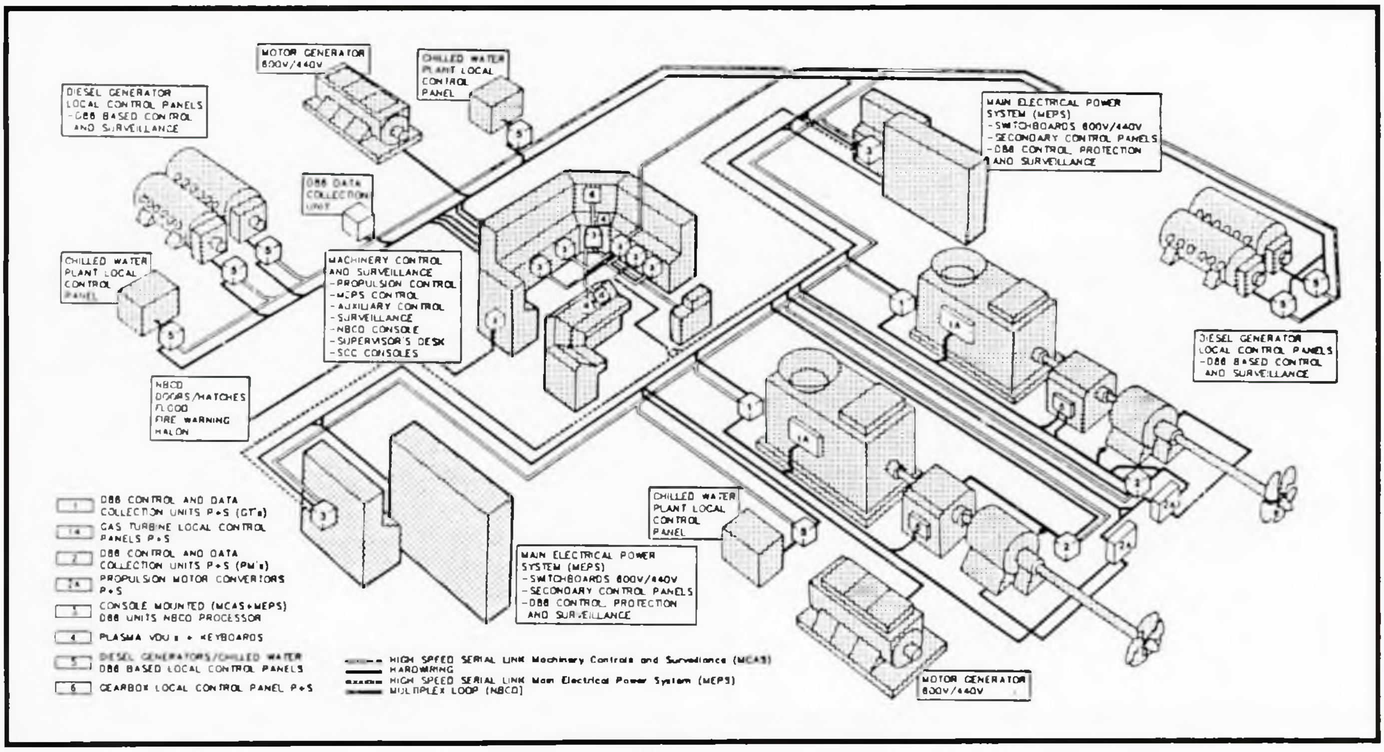

Fig 1: Type 23 Frigate – control system

The machinery installation selected to satisfy these requirements is the twin shaft CODLAG configuration (combined diesel electric and gas turbine). The layout is influenced by many factors including available space, system design, vulnerability, submersibility, etc (see Fig 2).

Two RR SM1A gas turbines, each rated at 12.75 MW, provide the boost power and, in combination with the two thyristor controlled 1.5 MW dc electric motors, provide the power to achieve the required maximum speed of over 27 knots. For low speed operations the electric motors are used on their own and in this state the ship can achieve about 16 knots on only 3 MW.

The selection of fixed pitch propellers for minimising underwater noise has meant that the electric motors are employed for manoeuvring astern, thus removing the need for a complex reversing gearbox.

Electrical systems

The highly integrated nature of this unique design demands very reliable and compatible control systems.

The systems are:

1. main electrical power system (MEPS).
2. electrical propulsion system.
3. machinery control and surveillance (MCAS) system.

A very quiet, cost effective, simple and reliable dc propulsion motor operates at 750 V which, allowing for rectification and control, requires ac power to be generated at approx 600 V ac. The four 600 V, 1.3 MW diesel generators operate in parallel to optimise usage, unless action damage dictates otherwise.

Two 945 kW motor generator sets provide and isolate the 440 V system from the 600 V system which may be subject to fluctuation caused by the propulsion system. Each motor generator is started direct-on-line on one or more diesel generators (see Fig 3).

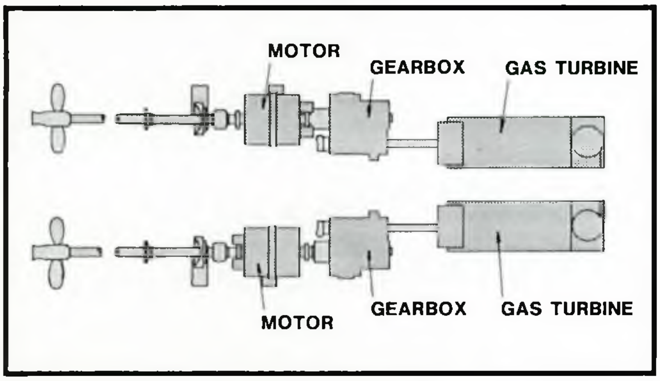

Fig 2: CODLAG arrangement

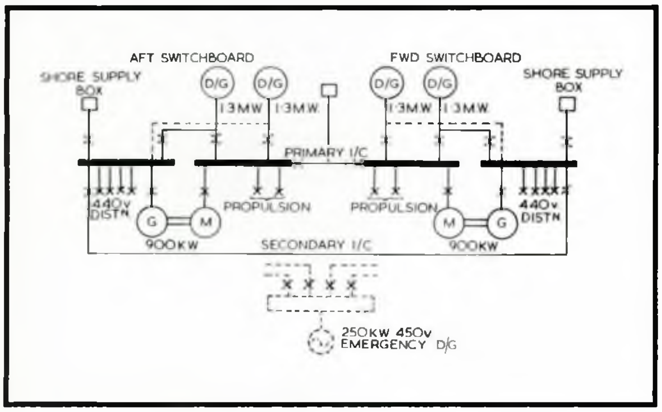

Fig 3: Electrical system

The Type 23 Frigate has five fire zones, each zone being provided with at least one electrical distribution centre (EDC). The number used depends upon the number of loads and the power demand within a particular zone. Each EDC receives a bulk power supply from the forward and aft 440 V switchboards and distributes power within a zone where consumers are classified in order of importance to assess the degree of supply integrity required. The lowest category is automatically shed under specified overload conditions.

All diesel generators can also provide 1.1 MW of power at 440 V, if required. A 250 kW emergency diesel generator is fitted. One design challenge was to enable up to four diesel generators to operate in parallel in both steady state and dynamic conditions in a stable fashion. It was concluded that in addition to the excellent load sharing capability of the diesel generator, a superimposed power management scheme was required, referred to as MEPS.

The key features of MEPS are:

1. it is microprocessor based.
2. centralised control and surveillance is provided in the ship control centre.
3. three levels of control are provided.
4. data links and hard wiring are used.
5. the secondary electrical control panels in the switchboard rooms are the principal fall back operating stations.

The principal MEPS functions are to share accurately the active power loading between the running diesel generators, dynamically and statically, and thereby maintain the frequency of the 440 V system within specification. MEPS also protects the system and ensures system surveillance.

The electrical propulsion system is simple in concept and the main features are that smooth dc is supplied from a thyristor converter and reversal of motor direction is by means of field reversal.

SIMULATION AND SHORE TESTING

The almost total reliance of any warship, and in particular the Type 23 Frigate, on its electrical power system has brought a need to analyse the behaviour of the propulsion system, especially under transient and fault conditions, to ensure that instability and possible blackouts do not occur. Marine power systems operate as finite bus-bar systems and consequently transients are of great importance, particularly if large distorting loads are supplied and when individual loads are large compared with the installed generating capacity of the ship; both of these types of condition are to be found in the Type 23 – with harmonics from the 6 pulse thyristor converter and motor generator set loads.

Two areas of power system development which have been of major importance to the Type 23 design and programme are simulation and shore testing.

Several very powerful and flexible computer programmes have been developed which can analyse and predict the response of the power system to a wide variety of transient and fault conditions and, in addition, whole ship propulsion performance can be studied in depth by simulated means. Both of these areas have been examined in great detail during the design stage of the Type 23, but the value of being able to comprehensively test hardware under realistic conditions outwith the constraints of a ship have also been recognised.

There was therefore a requirement to conduct a series of studies to confirm the validity of this novel system. This included:

1. overall ship computerised simulation modelling.
2. a shore test facility – identified as the Combined Test Facility.
3. Preliminary basin trials using brake wheels.

Each will be discussed in turn.

OVERALL SHIP SIMULATION

This computer model was developed and validated using the latest design data along with the latest design model information of various plant items from which a detailed dynamic analysis could be carried out.

The study produced results covering the following topics.

1. Steady state performance – over a range of propulsion drive operational modes.
2. Changeover sequences – between all normal drive modes. Examination was carried out of the demand control schedules and transient analysis under all manoeuvring conditions for safe machinery operations and satisfactory ship manoeuvring performance. The shaft brake was used in emergency conditions to improve the ship's stopping performance. Investigations were also made of failures of the transient brake, the synchro-self-shifting (SSS) clutch and electrical machinery.
3. Finally brake wheels were investigated as substitutes for propellers during initial powering trials.

   Brake wheels are essentially paddle wheels, circumferentially shrouded but open at the sides which are temporarily fitted in lieu of propellers. They are designed to absorb power in a similar manner to the ship's propellers, but they do so without producing thrust. Therefore they permit the ship's main propulsion machinery to be run at significant power levels during 'basin' trials.

Traces of the system response produced under simulation conditions illustrate some of the machinery characteristics as follows.

Crash stop (electric motor drive)

In the propulsion motor drive crash stop manoeuvre, the propulsion demand lever is moved initially from full ahead to full astern. The field current is reduced to ensure the motor power follows the demand and then increases again as the power falls below the demand with reducing field.

As the shaft speed passes through zero it is held by stiction for a short time, until the ship speed and hence propeller torque reduce sufficiently to allow it to break away astern (see Fig 4).

This demonstrates the regenerative phase of the propulsion motor. The propulsion motor cannot reverse the shaft rotation until shaft speed is low. Therefore it acts as a generator feeding power via the converter to the high voltage system. The armature current remains constant at its full value throughout associated with the constant motor torque (see Fig 5).

Crash stop (from CODLAG drive full ahead)

At the start of the manoeuvre, the propulsion demand lever is moved to full astern. The power turbine and the propeller shaft speed decrease together with the SSS clutch engaged. The SSS clutch disengages and locks out automatically either during deceleration or with transient brake assistance when the power turbine reaches idle fuel conditions, at which point regeneration of shaft power into the ships supply system commences (see Fig 6).

The motor starts to regenerate but the power is limited by the regenerative power limit which is equal to that consumed by the motor generator sets and the ship's services, although there is a small transient overshoot. As the ship speed reduces the regenerative power decreases and the armature current increases (see Fig 7).

'Stop – CODLAG ahead' (a rapid acceleration from stop)

At the start of the manoeuvre the gas turbine is running at idle with the SSS clutch locked out and a stationary shaft. The

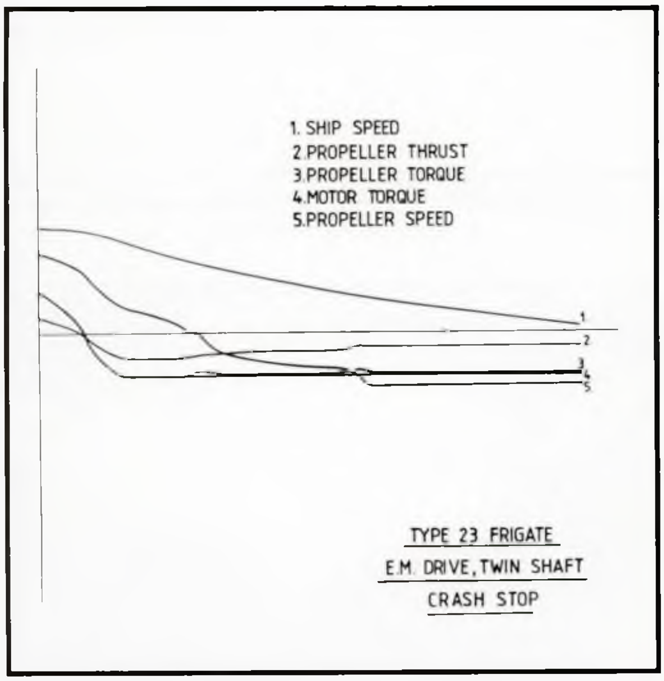

Fig 4: Type 23 Frigate – electric motor drive, twin shaft crash stop

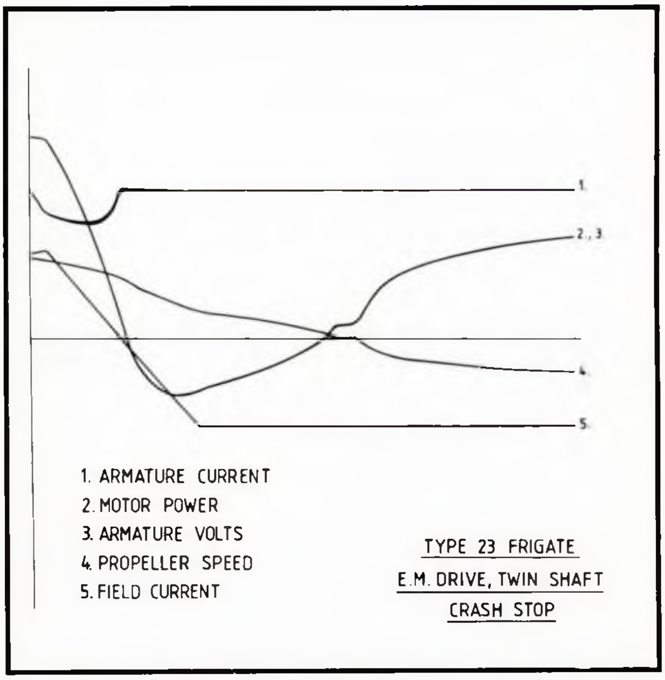

Fig 5: Type 23 – Frigate electric motor drive, twin shaft crash stop

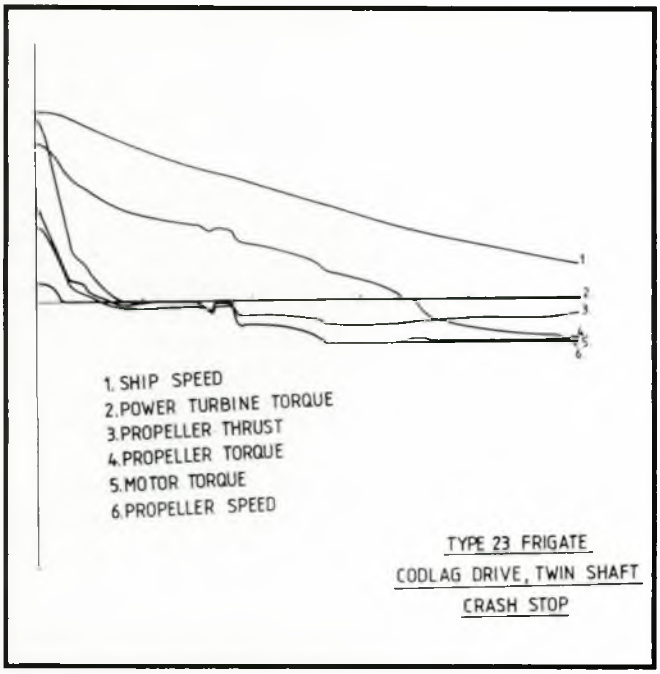

Fig 6: Type 23 Frigate – CODLAG drive, twin shaft crash stop

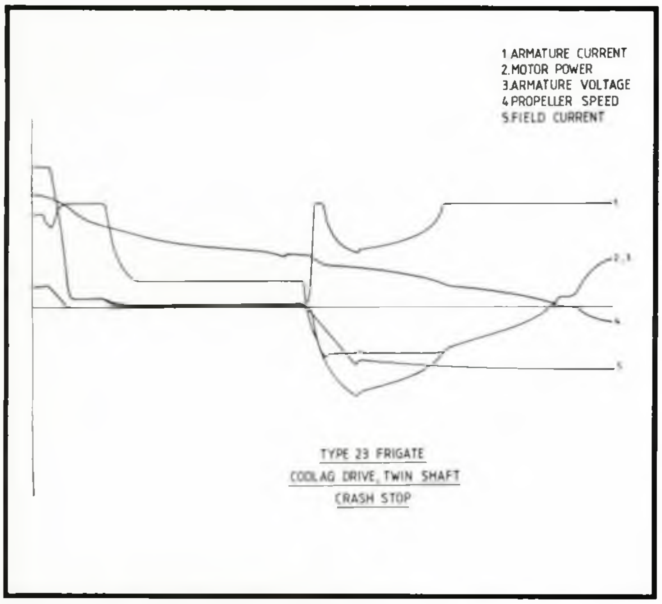

Fig 7: Type 23 Frigate – CODLAG drive, twin shaft crash stop

propulsion demand lever is put to full ahead. The shaft rotates as the motor current increases. After 5 s CODLAG is selected (see Fig 8).

Motor torque reduces when the electric motor exceeds its design state of maximum power and speed. This is induced at high CODLAG powers to prevent the motor power exceeding its designed value (see Fig 9).

COMBINED TEST FACILITY (CTF)

A shore-based test facility designed to evaluate the performance of the Type 23 Frigate electrical power and propulsion system was installed, commissioned and tested between August 1985 and February 1986 at the National Engineering

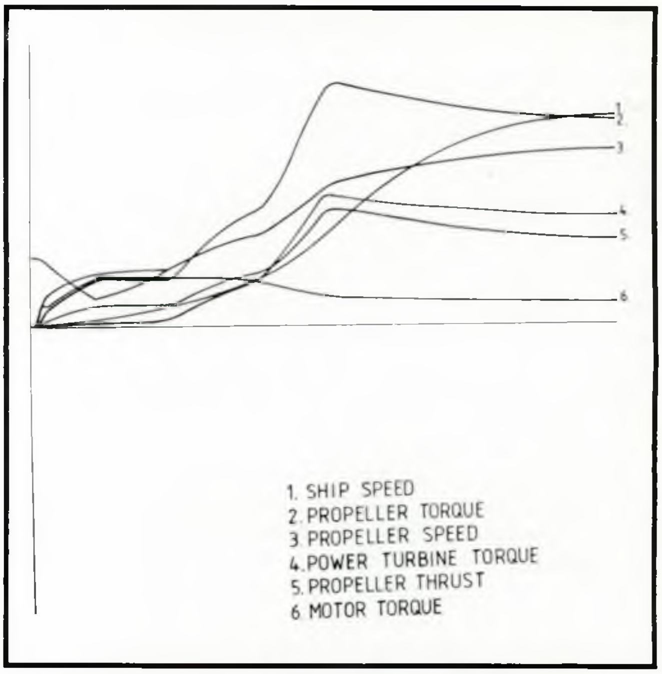

Fig 8: Type 23 Frigate – twin shaft acceleration from zero to CODLAG full ahead

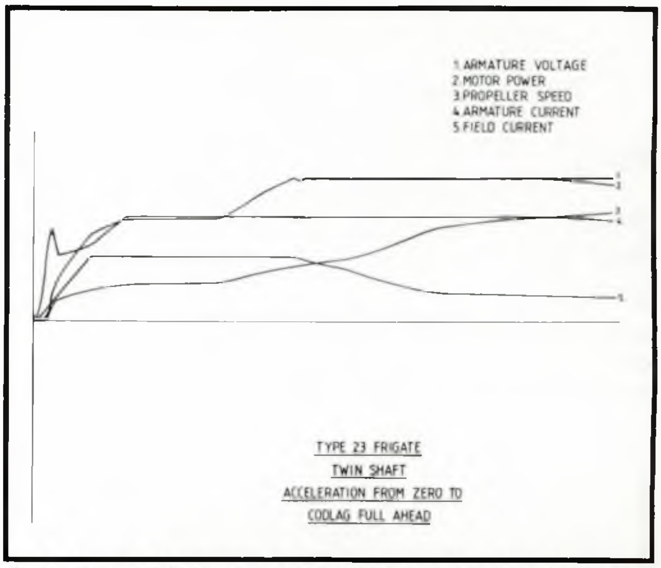

Fig 9: Type 23 Frigate – twin shaft acceleration from zero to CODLAG full ahead

Fig 10: Combined test facility, East Kilbride

Laboratory (NEL), East Kilbride. As the trials had to be completed within cost targets the time spent at the site was controlled and a full programme of tests was agreed before work commenced (see Fig 10).

The CTF provided an opportunity of bringing together some of the major items of the Type 23 plant prior to fitting at the ship and testing these as a system as near to ship operating conditions as possible.

The effect of the converter on the 600 V ac system using traditional design techniques was extremely difficult to predict and therefore a scenario of tests and failure modes were drawn up that had to be demonstrated before the system was installed in the ship. This included the ability to stop the ship, carry out crash stop/reversal manoeuvres and start the motor generator set.

The CTF had several main objectives.

1. To ensure that the dynamic and steady state performance of the Type 23 electrical power and electrical propulsion system met all design performance targets under both normal and fault conditions.
2. To ensure that the quality of power supplies for the 440 V power system met all the requirements under a wide range of non-linear load conditions [ie for weapons, communication and static frequency changer (SFC) based equipment], including electromagnetic capability (EMC) measurements.
3. To build up a powerful data base in the above two areas that could be used ultimately to facilitate improved design codes.
4. To commission and test full-scale Type 23 hardware.

Equipment

The CTF comprised half the ship's set of the electrical propulsion system and a device called the 'hull simulator' as a dynamic torque inducer.

The arrangement consisted of two diesel generators, a motor generator, a switchboard and secondary electrical control panel (SECP), a converter and propulsion motor, an eddy current brake, and two dc machines (which could be operated in the generating or motoring mode; see Fig 11).

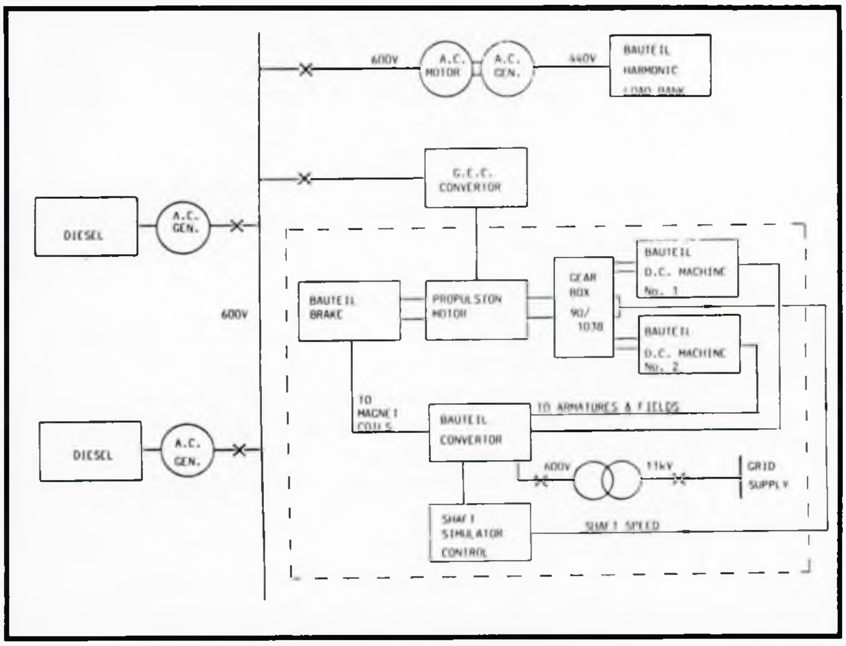

Fig 11: CTF equipment arrangement

Hull simulator

A 'hull simulator' produced for the CTF was designed to give the full range of propeller transient and steady state torques that the shaft would be subjected to during ship-based electrical power propulsion drive.

This device meant that all simulations in terms of hull and propeller characteristics were derived from shaft speed.

The various requirements of supplying and removing power from the rotating shaft and the associated torque and speed implications were catered for by the combination of an eddy current brake and separately excited dc machines which were capable of generating torque of the required magnitude and sign.

These torque generators were controlled so that their total torque corresponded to that which would have been imposed by the propeller under various conditions.

Under rapidly changing propulsion system conditions, for example crash reversal, the dynamics of the ship/propeller shaft system demanded that the brake, which was absorbing power from the shaft, would be 'phased out' and the dc machines then 'phased in' to supply power to the shaft until the shaft reversed direction. The dc machines then operated as generators taking power from the shaft. As shaft speed built up the brake was 'phased in' to simulate the propeller load.

Tests

To control the initiation of the tests and capture the necessary data, an extensive control and instrumentation system was fitted. A purpose-designed event controller initiated the tests and results were stored on a multi-channel tape recorder. On completion of each test the tape recorder played back to a databus to which was connected a computer, visual display unit, plotters, printers and digital disc drives for later data analysis and storage.

Some 300 tests were carried out at the CTF. These tests covered the following.

Ship manoeuvring transients

These included stop to full ahead, crash stop reversals for various levels of regenerative braking and very low speed ship manoeuvres under heavy sea state conditions.

Motor generator starting transients

There were many tests that came under this heading, all designed to test comprehensively the load acceptance capability of the diesel generators.

Despite all the calculations and simulation work there was a big question mark as to whether a single diesel generator could start a motor generator set which had a power output and inertia of nearly two-thirds that of the diesel generator. It was demonstrated that this motor generator set could be started from a diesel generator which had been running for some 30 s from a cold (5°C) start condition (see Fig 12).

Another test carried out was an investigation of the situation of one diesel generator being fully loaded by the propulsion motor, and then the motor generator set being started. The design of the propulsion motor converter regulator enables it to detect the fall in frequency that occurs in this condition, virtually reducing instantaneously the motor power

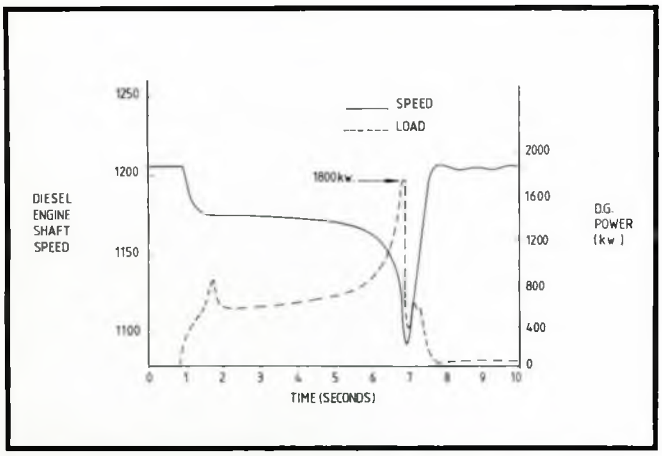

Fig 12: Type 23 Frigate – motor generator start on a cold diesel generator

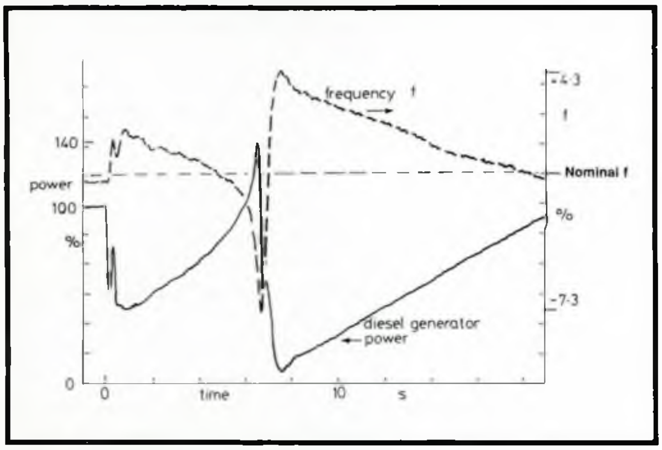

Fig 13: Motor generator start on one diesel generator fully loaded by propulsion motor

levels until the start is complete, and then slowly adding propulsion motor power back on to the pre-starting level. (In practice the ship would slow down slightly.) The recording system was able to capture signals from the moment the motor generator started and as the waveform changed from the 'sand castle' form, associated with the converter, to nearer a sine wave! (See Fig 13.)

Excitation failures

A wide-ranging review of the automatic voltage regulator (AVR) performance under failure conditions was successfully completed.

Fuel failures

These fuel failure tests were undertaken to establish the operational capability of devices such as the reverse power relay and the fuel fault detection system within the SECP.

System protection under fault conditions was very important and many tests were aimed at checking the effect of diesel generators tripping from loss of fuel, over-fuelling, under-fuelling, etc (several types of AVR fault).

A straightforward 'common' fault is a diesel generator trip on a two diesel generator system. Power supplies to essential weapon and ship services are well protected by the much more reliable motor generator set; albeit the ship might slow down until another diesel generator is started. However, the operator in the ship control centre has the option of putting the priority for power supply to the propulsion motor and shedding non-essential ship's load if the ship is in confined waters (see Fig 14).

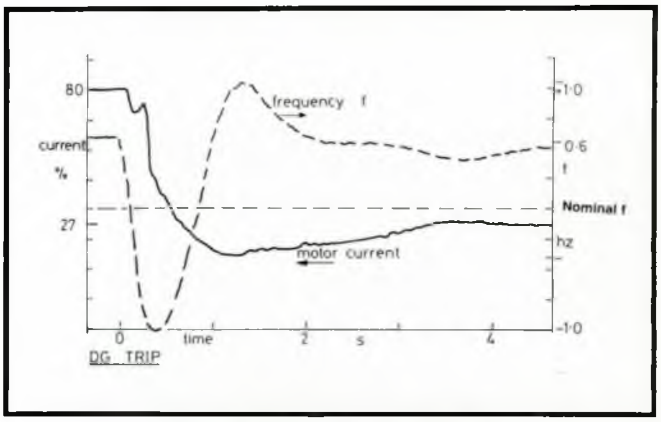

Fig 14: Diesel generator trip

The propulsion motor converter regulator receives information from a number of sources. It reads the power level of the other motor, the number of diesel generators running from the breaker states, the power being delivered to ship's services, and the power levels at which the ship control centre operator allows the diesel generators to be run. The ship control centre supervisor can control the maximum diesel generator power level to 85%, 100% or 110%. The first level is used during normal running, the second level when in confined water, and the last level during emergencies.

The propulsion regulator then calculates the maximum power that the motor can supply for the specific plant condition, and if the power demand exceeds that value, the propulsion motor is prevented from exceeding this limit by the 'power limit system'; a warning is produced in the ship control centre so the supervisor can decide to increase the number of diesel generators, start gas turbines or inform the bridge.

Short circuits and mal-synchronisation

Investigations were made into various short circuits. There were seven tested in all (phase to phase and 3 phase) – far more than the ship would see in reality. However, the most demanding test was that of a mal-synchronisation. The incoming diesel generator was set at 120 deg out of phase with the heavily loaded diesel generator when its breaker was closed. This was initiated by switching two sensing leads on the synchronisation control circuits. The result was dramatic power swings of 3-times the maximum output of a diesel generator between each diesel generator. This excess power came from the inertia of the diesel generators and the system. Most important, a black-out did not occur and examination of diesel generators afterwards revealed no defects from this controlled abuse.

Harmonic investigation

A special load bank was designed to simulate the harmonic impedance and power flow characteristics of all the weapon systems connected to the Type 23, 440 V system.

CTF results were also used to verify the overall simulation model. For example, the motor generator start test was used to validate both the diesel speed and electrical transients of the diesel engine model.

PRELIMINARY BASIN TRIALS

A brake wheel was attached to each shaft, in place of propellers, so that power could be absorbed without thrust.

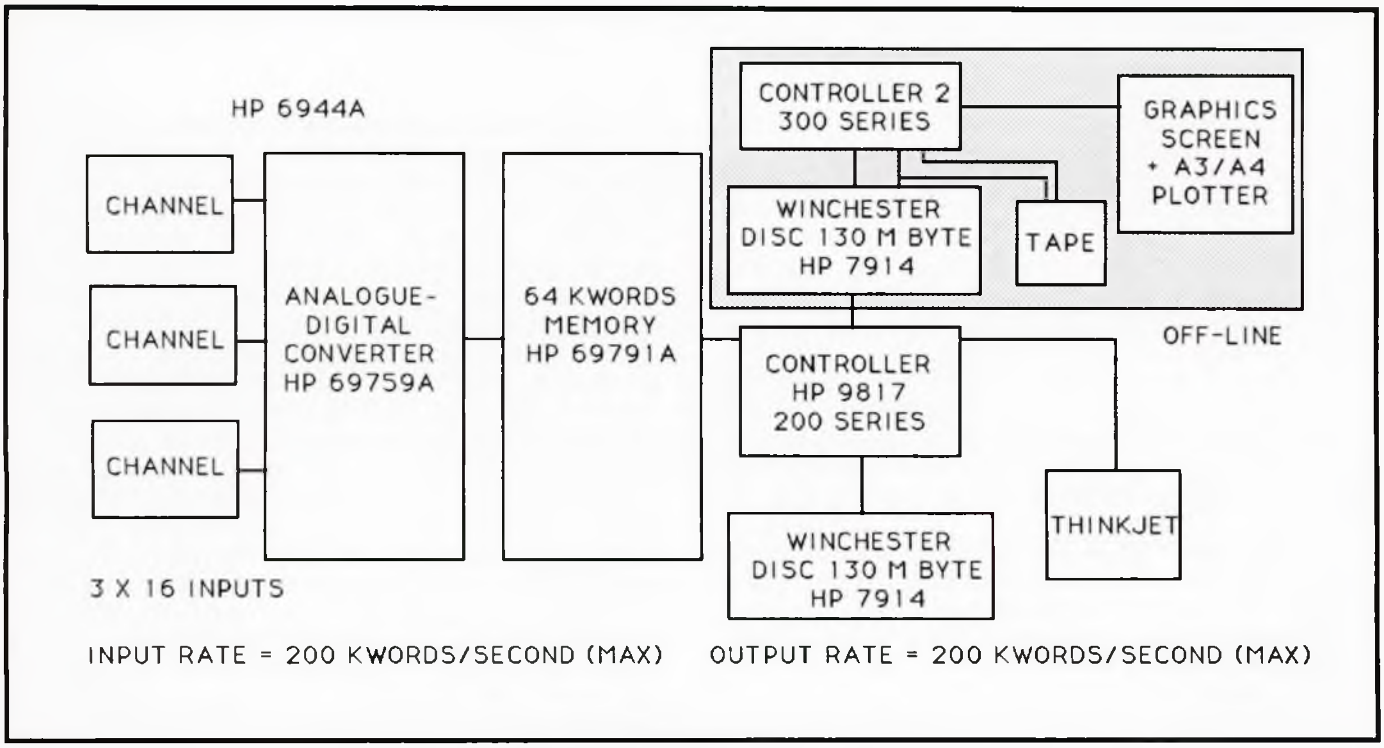

Fig 15: Data acquisition system

The brake wheels were designed to produce the same characteristic as the designed Type 23 propellers. Incorporated in these trials were:

1. propulsion motor and converter dynamic trials.
2. Spey engine, propulsion motor and shaft line trials.
3. propulsion motor changeovers.
4. propulsion motor basin trials.
5. CODLAG basin trials.
6. noise and vibration assessment.

A data acquisition system was installed on the ship to assist in localising the source of equipment/system problems during preliminary basin trials, official basin trials and contractor's sea trials and also to produce data from which the performance of the CODLAG system could be evaluated.

This data acquisition system was based on Hewlett–Packard equipment operating both on 'on-line' and 'off-line' systems.

The 'on-line' system comprised a multi-programme with a dedicated controller collecting data onto a Winchester disc.

The 'off-line' system processed and displayed, for analysis, the recorded information (see Fig 15).

CONCLUSION

Yarrow utilised modern simulation and shore testing techniques, more so than for any previous contract, from which design information was progressively refined as data was verified. As a consequence, there is a high level of confidence in the propulsion system and designers have been able to identify problem areas and initiate design changes at an early stage to further improve the system.

The most recent and most valuable data has been provided during the official basin trials where the propulsion plant was operated at the maximum permissible power alongside the quay wall, showing the benefit of the brake wheels (see Fig 16).

Fig 16: Brake wheels

THE WAY AHEAD

The performance of this CODLAG propulsion system will be confirmed during contractors sea trials and current indications are that the specified performance will be met. This being the case, Yarrow will be fully confident that the modelling and shipborne test results available will make it very unlikely that further shore testing will be required for future propulsion plants of this type. Yarrow would then take a long, cool look at the design and development of a superconducting plant.

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Discussion

R Barnes (Robert Barnes Consulting Engineers) I read this paper with considerable interest, both past and recent, having been responsible for propulsion control system trials in the MOD 20 years ago, and having last autumn participated in an independent evaluation, including sea trials, of *HMS Challenger* (the Navy's other major surface vessel fitted with diesel electric propulsion). In between I participated in the failure mode effect and criticality analysis of the Type 23 chilled water plant 3 years ago.

Background. This paper follows on very well from the 1983 paper on electrical systems in warships by Mr A J Scott (ref 1 below). In particular, his supplement on the evolution of the Type 23 system design is very helpful in understanding this paper. I am a little surprised that it is not referred to by the author.

Dc motor. Could the author provide a little more detail about the propulsion motor? I suspect that it may not be quite as simple as described. Is it series/parallel, or straight series (shunt) wound? Are there separate windings for regenerative braking? Was the armature locked shaft condition tested in the CTF (Combined Test Facility)?

Diesel generators and MEPS. *HMS Challenger*'s trials indicated to us that the power management system (PMS) programme of any naval ship must be correct to be of use. There are some interesting comparisons with the comments in this paper. In particular:

1. The MEPS/PMS appears to be intended as an operator-assist system in both ships. In practice *Challenger*'s PMS can be either 'off' or 'on' and in complete control of the generators and propulsion motors. There appears to be a contradiction between the statement on the second page of the paper defining the system's functions, and that on the sixth page stating . . .'that the supervisor can decide to increase the number of diesel generators . . .'.
2. *Challenger*'s PMS imposes time restrictions, up to 20 min, on restarting the plant after shutdown.
3. My impression was that skill levels of ships' staff are very high, and generally better than those of the PMS we saw. The PMS was originally conceived for dynamically positioned offshore vessels in the commercial fleet.

Could the author elaborate on the three modes of operation and say what advantages the MEPS is likely to give the Type 23 operators? Will it justify its cost, maintenance and space? Will it also provide an indication to the bridge console and SCC of 'spinning reserve'?

Distribution. On the assumption that the secondary power interconnecter is open with both motor generator sets supplying their own switchboards, have shore trials confirmed the need for very high breaker reliability needed to close and maintain uninterrupted ship's supplies, should one motor generator set trip? This is potentially a very weak link in this system. Breaker maintenance is of course very important in this interconnecter.

Fuel fault detection. I should be very interested to hear what form this takes and what properties are sensed.

Shore testing (CTF). It would be interesting to hear more fully the reasons for not constructing a full shaft line of machinery with the gas turbine, clutch and gearbox. Also relevant is the paper's penultimate sentence, which I read with some reserve.

Past naval experience, particularly with the Y102/Y111 COSAG plant, where shore testing was geographically diverse (G6s and gearboxes at Metrovick, Trafford Park; steam boiler and auxiliaries at Haslar; steam turbines at English Electric – refs 2 and 3 below), has shown that serious reliability and safety problems arise in County Class steam plants during the first 2 or 3 years of operation – unplanned downtime was 1 year in every 2. Subsequently, major redesign of the feed system was needed. In the Type 42/22/21 CODOG plant, following the 1965 Defence Review, time prevented shore testing; but *HMS Exmouth*'s conversion contributed considerably towards achieving a reasonable plant (ref 4 below). The CAH (cruiser/carrier) plant was fully shore tested by Rolls Royce and has proved satisfactory. Ref 4 below concludes: 'However, the greatest contribution to the high operational reliability achieved to date must surely stem from the extensive trials at the Shore Test Facility at Anstg. . . .' Therefore, one might say here, that omitting the gas turbine and transmission train comes from overconfidence: was the prevention of SSS clutch failure (described in the paper, third page) validated in the CTF or during basin trials, for example? Hopefully, this has been adequately covered in the design. However, experience has taught us – expensively at times – that if we test and debug the plant onshore, then at sea something will inevitably occur that we didn't think of. Could the author comment further on this point please, and on current philosophy? The chilled water plant did nearly 1000 h shore testing at the makers. Could he also give us the total running hours on the CTF, and state whether it has been able to predict target MOD reliability requirements?

Can he let us have some idea of any real faults that occurred during trials?

One criticism: Fig 10 of the paper, the picture of a large shed (revealed to be a tent in the presentation) is rather disappointing. Why not picture the actual plant?

Validation. Considering that validation occurs in the paper's title, it was disappointing not to have the comparison plots of CTF response published with Figs 4–9. Could the Figures shown in the presentation be produced in the author's reply please?

Data acquisition. This is very important, as the author states, particularly for fault diagnosis. This lesson was learnt through not fitting a data system in *HMS Exmouth*, initially. In MOD(N) we did a very satisfactory retrofit in 1971/72 (ref 5 below). During operations a year or so later, it paid for itself and a new frigate on the same day, by enabling the diagnosis of a small telemotor fault in the controllable pitch propeller to be made and cured in 3 h, indirectly preventing an emergency docking and re-deployment of the rest of the 2nd Frigate Squadron. From this system the standard DDR was developed; pictured and described by N D Anderson in *MER* (ref 6 below). I hope that a similar DDR has been or will be supplied for all Type 23s, as I do not consider that a digital scanning data logger is adequate means for analysing and interpreting transient manoeuvres in these advanced power plants.

One result from the failure analysis of the Type 23 chilled water plant, we found, was that insufficient use was being made of the D86 supervisory control system for fault diagnosis. It would be nice to know, therefore, how the results of both CTF and basin trails so far, have been used to provide this information. Have we reached 'expert system' stage yet?

Evolution – The way ahead. The authors comments on a superconducting (SC) CODLAG plant are fascinating, and enough to retain my membership of the Institute for many years to come! Quite a considerable amount of work on an SC drive for minehunters was done 20 years ago in Bath, and it would be interesting to know if the development was connected – hopefully in another paper one day. In the meantime, the author and presenters are to be congratulated on producing a very interesting and provocative paper; and so is the Ship Department for producing another highly innovative and hopefully successful design concept. Despite the advent of the NSR90 Euro-Frigate project, I very much hope the Type 23 will not be the last major warship plant we produce in Great Britain by our own efforts.

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D R Wilkinson & J D McIver (Yarrow Shipbuilders Ltd)

Dc motor

1. The propulsion motors are of an extremely simple design being shunt machines with very low electrical loading parameters. Hence there was no requirement for a compensating winding. Noise reduction was a high design priority and various physical features coupled with low loading has resulted in a very quiet machine. The armature and field circuits are fed from separate 6-pulse thyristor converters with significant smoothing embodied in the outputs, reversal being accomplished by changing the polarity of the field current.
2. The propulsion motors may be operated as dc generators, using the basic armature and field windings to supply dc to the armature converter/inverter system, thence ac to the ship's 600 V system. The amount of regeneration is automatically limited to a proportion of the ship's 440 V load or, alternatively, to a manually set limit.
3. A stall protection system is included in the design which opens the converter ACB if a stall persists for more than a pre-set time and current.

Diesel generator and MEPS

1. The MEPS is designed to supervise and control the operation of the 600 V system which consists of up to four 1.3 MW diesel generators running in parallel. This includes synchronising, load sharing, protection and supervision. The loop relating to normal starting and stopping of diesel generators is left open, that is, command has the decision to increase or decrease the number of diesel generators in use, responding to the perceived situation or warnings from the MEPS.
2. There are no time restrictions on restarting plant after shutdown. This would be unacceptable in the Type 23 design.
3. The authors would agree that skill levels of the Type 23 ship staff are observed to be very good. They have not been called upon to operate the ship yet as this is done by YSL, but having attended system instruction at subcontractors, they exhibit a broad and deep knowledge of the ship and its systems.
4. In the ship control centre (SCC) mode of control, a single watchkeeper can operate and supervise the entire propulsion control system, MEPS and auxiliary systems from the displays and controls on a centralised control console. The operator's activities are monitored by a watch supervisor. In this mode of control the main switchboard rooms are unmanned and the MEPS ensures that the 600 and 440 V systems operate in the specified manner.
5. The next level of control of the electrical plant is from the forward and aft main switchboards. Equivalent local control panels are provided for the gas turbines, diesel generators and propulsion motors and in this régime, local watchkeepers are required at all these control stations with voice communication to integrate operation. This is a fall-back method of operation as it is manpower intensive.
6. A third level of control is possible which bypasses all MEPS control, eg ACBs would be operated directly, check synchronising would be used, and protection would be limited to that provided by the ACB trip units. It is anticipated that the high reliability predictions for the MEPS will not require this method of operation to be invoked frequently.
7. It will be evident that the use of an MEPS greatly reduces the workload of the watchkeepers, particularly in high activity scenarios, leaving watchkeepers free to attend to more urgent matters.
8. Regarding costs, quite a large proportion of MEPS costs is the cost of the air circuit breakers. The remainder consists of electronics, data links and panels, which are not excessively costly. In terms of the resultant reduction in operators and watchkeepers, the MEPS cost is more than justified.
9. There is no indication of 'spinning reserve' to the bridge but 'power available' indication is provided at the SCC and propulsion converter local control panels.

Distribution

1. The shore trials of the Type 23 propulsion system were limited to the 600 V electrical propulsion system, hence no 440 V testing took place. Extensive availability, reliability and maintainability studies were carried out on the 440 V system. However, for given targets, it was established that attainable MTBFs etc, for equipment were required, including the ACBs. The Type 23 has two types of dual supply to equipment classed as vital *viz*:
   a. automatic changeover switches (ACOS) and,
   b. remotely operated changeover switches (ROCOS).

   The former equipment is used for the highest integrity supplies.
2. The use of ACOS is well established in Royal Navy ships and, provided the normal and alternative supplies are independent in all respects, a very high integrity supply is automatically available to selected equipment. ROCOS are manually operated remotely and are in widespread use for those services or equipment which can tolerate a short break in supply. Battery-backed transformer rectifiers and some static frequency changers also provide uninterrupted power outputs.

Fault detection

1. It can be shown that the greater the number of protection systems used, the less will be the overall system reliability, hence a fine judgement has to be made about the number used. The principal faults detected include:
   a. for 600 and 450 V systems, undervoltage, overcurrent and reverse power.

b. earth faults.
c. for the 600 V system only, a limited biased differential protection system is provided.
d. excessive current and/or power demands results in shedding non-essential loads.
e. electric propulsion power demand is automatically limited to power available.
f. power available to electric propulsion systems from diesel generators may be limited to 85, 100 and 110% of diesel generator capacity. In the latter case, non-essential loads are automatically shed also.

Great care was taken to ensure system selectivity.

2. All the features are aimed at ensuring the diesel generator protection is maximised at all times.

Shore testing

1. The authors do not dispute Mr Barne's erudite views on shore testing and they understand and fully support the data on the various propulsion plants listed. YSL costed such a proposal for a plant of a similar configuration to the Type 23 Frigate and the cost was very high, certainly far outwith any MOD(N) funds then available. Only after considerable YSL pressure, was a very limited funding made available to set up a single shaft set of the electrical propulsion system.
2. The omission of the gas turbine and reduction gearbox from the CTF was certainly not overconfidence by YSL, but it does clearly reflect the risks that private companies now have to take on MOD(N) contracts.
3. The remaining YSL option was to undertake extensive modelling of the CODLAG plant and this, coupled with experienced engineering judgement, is an acceptable substitute, up to a point. Such analysis highlighted a number of areas where limits, rates and sequences had to be modified and these were introduced into the plant. But clearly physical effects like thrusts, auxiliary circuits of equipment, critical speeds etc, cannot be fully replicated and risks must remain, but that is part of the cost of being in the warship design business.
4. As a consequence, the rationale decided by YSL is to maximise the analysis of real plant at a CTF, combined with extensive analysis, modelling and engineering judgement, programmed such that the earliest possible running of the combined plant on brakewheels can be achieved and the fitting of the propellers is postponed to the very latest time possible. All equipment and systems are to be subjected to searching and rigorous factory testing.
5. Thus far, this strategy has been successful but the introduction of propeller and ship dynamics has yet to be verified.
6. The authors note with envy the option which the CAH enjoyed regarding shore testing. YSL are unaware of the real cost of this work but it will probably represent a large fraction of the cost of a Type 23 Frigate.
7. The CTF did not set out to prove quantitative reliability targets, rather to test the integrated performance of constituent equipment from various suppliers: GEC large machines, GEC Industrial Controls, Paxman Diesels, Vosper Products Limited, Laurence Scott and Electromotors, Brush Electrical Company, Marconi Radar Systems. In this way any necessary corrections could be introduced at an early stage and before the ship installations were complete. All this equipment and cables were refurbished and used in ships of the Class.

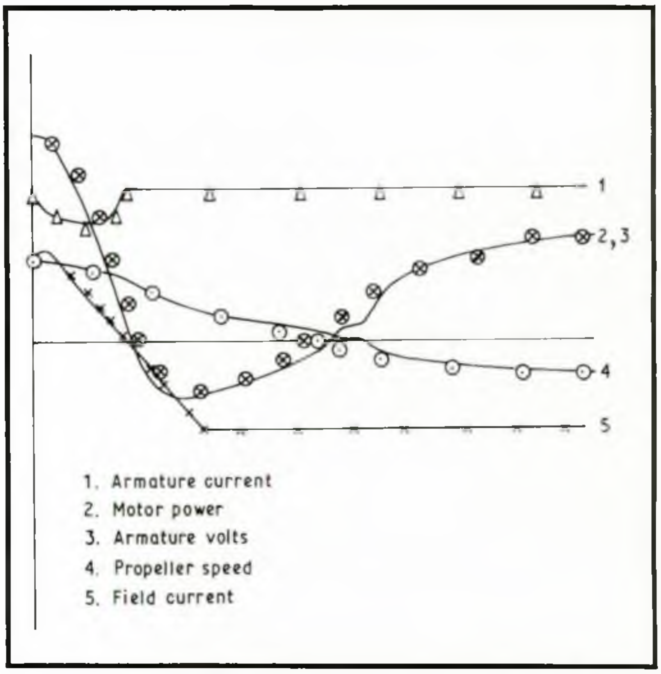

Fig 1: Type 23 Frigate electric motor drive, twin shaft crash stop

8. Fig 1 below superimposes some CTF results onto Fig 5 of the paper showing very good correlation for armature current, field current and motor power. Some early difficulty in the CTF brake is in evidence in the propeller speed curve where the phasing of the electromagnetic brake and the two dc drive motors was incorrect. The absence of shaft stiction is also in evidence in the CTF results. As there was no CODLAG drive at the CTF, no points of comparison exist.
9. A photograph of the interior of the CTF 'Test House' is included (Fig 2).

CTF faults. The CTF equipment and systems performed largely as YSL specified, allowing that a number of interface incompatibilities were identified and corrected. Also many minor errors within equipment were identified and corrected, but on the whole, very valuable data were gained regarding rates, limits and set points. One lesson learned, however, was that analysis of results must not be deferred at the expense of carrying out the programme. Leaving the analysis until later leaves issues unexplained and provides no opportunity to repeat tests. At this point YSL has to applaud the work of their subcontractors in producing first class equipment to specification.

Data acquisition. The D86 system is permanently fitted to the Type 23, and controls apart, it is used to monitor, record and print out much plant data. There is also a limited amount of DDR. The data acquisition system referred to here is a temporary recording system fitted to cover all ship trial results. It does monitor steady state conditions but its main virtue is to monitor large numbers of dynamic parameters. In the case of the Type 23 Frigate, 48 simultaneous parameters are monitored, stored and printed out, revealing cause and effect of many problems and thus indicating the likely source of a problem. This precise type of data is quite vital at sea trials where analysis and rectification must be done in the shortest possible time.

Evolution

1. The authors were involved in the superconducting application referred to, and with much of the support work at IRD. However, they were never fully convinced that this solution had found a problem in marine propulsion!

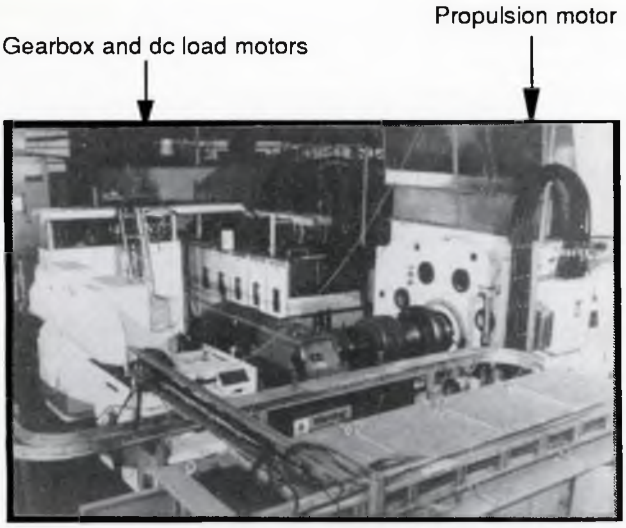

Fig 2: General view inside the CTF – propulsion motor in evidence

2. A gas turbo-electric system could be engineered now using high speed (6000 rev/min) generators, and cycloconverters with ac propulsion motors. This was one option for the NATO NSR 90 Frigate propulsion system and it was shown to be capable of fitting in an acceptable arrangement.
3. The authors believe that such propulsion plants are now at a stage when expert systems should be introduced. For complex plants, the logic of an event resulting in a likely solution or cause will be a great asset to the operator/maintainer. In other non-machinery systems also, such as fire and flooding, combinations of such events suggesting the optimum action will become quite vital as crew numbers reduce but they must be of the highest reliability and availability or else they will be self-defeating.

J K Robinson (LR)

1. In the system description the author mentions the machinery layout as being influenced by 'submersibility'. Would he clarify where the watertight subdivisions are located and to what extent the electrical equipment has degree of protection IPx7 to IEC529 (or equivalent)?
2. It is noted that a power management scheme was required (MEPS) and this was microprocessor based. What analysis was carried out, and system configuration found necessary, to achieve the desired reliability and availability levels?

D R Wilkinson & J D McIver (Yarrow Shipbuilders Ltd)

1. Submersibility. It was not the purpose of the paper to describe the many features which have been introduced to maximise the survivability of the Type 23 Frigate since this is the subject of other presentations to the Institute. However Mr Robinson's question can be answered very briefly by saying that the gas turbines are located in a different compartment from the propulsion motors so that the flooding of a single machinery space will not render the ship immobile.

   The watertightness of electrical enclosures cannot be simply described; it depends on essentiality and location. In some cases standards higher than IPx7 are applicable, but in other cases lower standards are perfectly adequate.
2. MEPS reliability. Extensive ARM and FMEA studies were carried out to ensure that specified targets would be met. These studies can be divided broadly into:
   a. equipment predictions/measurements by subcontractors on their equipment;
   b. using the results obtained from 1, system studies to determine the overall, cost-effective system configuration.

   Funding for ARM was very limited and some difficulty was found in deciding upon the optimum time to undertake these studies.

   As a result of these studies, which in absolute terms are acceptably accurate, the greater importance was found to be, in relative terms, an excellent means of determining sensitivity effects. Equipment and system configurations were amended to take account of the results.

T Blakeley (RN) A most interesting and thought provoking paper, lacking only in detail of the final phase, ie sea trial results – awaited with interest.

D R Wilkinson & J D McIver (Yarrow) In reply to Cdr Blakeley, YSL also await sea trial results, with even greater interest, and hope to present these results later.

R C F Hill (RN)

1. I am looking forward to having the Type 23 in service.
2. I am glad to hear of the good reliability of the Valenta diesel generators.
3. In the early 1980s MOD was criticised for 'gold plating' its warship designs. Does YSL feel there was any element of over- or under-specification in MOD's requirements for the Type 23?

D R Wilkinson & J D McIver (Yarrow Shipbuilders Ltd) Valenta diesel generator. The Valenta diesel engine with a 1.3 MW brush generator was the subject of extensive ARM and FMEC studies and the promised performance seems to have been achieved. This combination has been used considerably, and under controlled 'abuse' by YSL it has survived extremely well.

Type 23 specification

1. The propulsion plant specification was defined by a number of statements of technical requirements, some of which defined system requirements, others defined the requirements of equipment.
2. In future we would prefer to have system STRS in order to avoid the conflict that inevitably arises between system and equipment specifications, each of which have their 'sponsors'. There are certain system aspects in particular the electrical load sharing that could have been simplified and possibly extended to automatically start up additional generating capacity to meet increasing load conditions.
3. The machinery control and surveillance (MCAS) scheme appears to be over-complicated. But we would prefer to comment when we have some sea-going and hence practical operating experience of this system and its interface with the electrical power management system.
4. Generally we do not believe that the system was over-specified but it is inevitable that, over a period of 7 years, technology has not stood still and so the system and equipment look somewhat dated now.

R V Thompson (President, IMarE) I would like to thank Mr McIver and Mr Wilkinson for a most entertaining and informative presentation of the problems overcome in developing the Type 23 Frigate, suggested to be the most complex machinery arrangement involved in the RN Fleet.

Of prime interest was the value placed upon validating the overall system design by the use of a shore test facility which, because of budgetary constraints, was itself temporary, having been assembled in a car park in a tent!

I am of the opinion, which I have held for some considerable time, that the UK should build a permanent 'all-singing and dancing' shore test facility which would permit 'first of line' testing quickly and efficiently as appropriate, and furthermore could become a 'good little earner'! Perhaps the authors would care to comment.

D R Wilkinson & J D McIver (Yarrow Shipbuilders Ltd)

1. Cost constraints on the Type 23 project encouraged us to find other solutions to problems.
2. No doubt if cash had been available then a comprehensive shore test facility would have been erected and the plant tested to the n^{th} degree ashore.
3. In our opinion the areas of risk in this propulsion system were, primarily, in the electric motor and its converter and the ability of this system to cope with reverse power in static and dynamic conditions.
4. Having been involved with other shore-based testing plants it is essential, in order to maintain costs, to have a very clear plan of campaign and a termination date, otherwise the engineers will continue testing for testing's sake.
5. We believe that the computer-based system modelling that was carried out prior to the running of the plant in the CTF gave a very good prediction of the likely outcome.
6. It is obvious to us that computer simulation is the area where effort is best spent rather than in setting up shore test stations for very specific plants with limited application.
7. We would agree that a shore test station allows the plant mechanical interfaces to be sorted out well before these problems occur in the first installation. But having done it 'once' it is very questionable if all plants for each ship should be integrated ashore before installation in a ship.
8. It would be of more value to future engineers if they realised the power of computer simulation of plant performance and hence were able to appreciate the dynamic operation of a complex system and the constraints that have or will be imposed in order to make it operate with the ability/performance of the equipment.

R S Blackman (RN)

1. As someone who was associated with the Type 23 design in the early days may I first congratulate Yarrow Shipbuilders for developing the design successfully thus far. However, the paper's final paragraph infers that development has effectively been completed. Bearing in mind that the basic design was conceived by the Ministry of Defence, and was only partially developed when Yarrow became involved, it would be most interesting to learn how YSL would, with the benefit of hindsight, improve or enhance the original design whilst still meeting the original objectives for the plant as a whole.
2. On the subject of objectives, I note that the paper states that 'it was a prime objective to reduce both procurement and through-life costs'. This most commendable double objective is considered by many to have mutually in-compatible components. The search by the Ministry of Defence and their contractors for minimum procurement costs has received a fair amount of publicity. Can the authors state what specific measures have been taken in the development and construction of the Type 23 Frigate that will reduce through-life costs? Also have any of these measures resulted in increased procurement costs?

D R Wilkinson & J D McIver (Yarrow Shipbuilders Ltd)

1. YSL believe that the Type 23 propulsion plant, which contains many 'firsts' (first RN frigate with diesel electric propulsion; low noise requirements etc), has undergone its initial trials very well. After the sea trials period we will be evaluating the propulsion system objectively and therefore we are able at this stage to identify possible improvement areas to the original design concept.
2. Throughout the design and design development stage, reviews were carried out on ship critical systems and equipment. As a result the maintenance routines and spares holdings were defined. We believe that this has had the effect of reducing the through-life costs, but cannot readily identify an increased procurement cost.
3. The present propulsion plant configuration is the result of considerable optimisation, therefore it is not surprising that we have not found any major departures to obtain the specified performance. An interesting comparison is evident between the discrete component technology of the propulsion converter/regulators for example and other software-based systems. The former may be modified *in situ* if necessary and at little cost, whereas the latter require extensive time to correct and prove, and such changes are very costly. The authors are not saying the choice was incorrect, but '20/20 vision' would be useful if a re-appraisal was made.
4. With regard to contractual issues relating to design, experience has led us to conclude that an excess of interfaces can make life difficult. We would look critically therefore at the number of, and arrangements for, interfaces between all parties involved in the propulsion package.
5. Other features abound where unit costs rule supreme, eg health monitoring, bridge control of propulsion machinery, embodiment of trials, transducers and equipment, etc, which would enhance operation of the vessel.
6. Regarding the reduction of through-life costs associated with the propulsion machinery, the following are considered to fall into this category.
   a. The carbon brush debris removal system in the propulsion motors.
   b. The option of open or closed ventilation of the propulsion motors.
   c. Self-diagnostics to a limited extent will minimise the time for ship staff to effect repairs.
   d. Extensive MCAS monitoring and flexible presentation of data in the SCC.
   e. Electrical braking of the propeller shafts.
   f. Absence of an auxiliary steam system.
   g. Reverse osmosis plant for fresh water production.
7. A ship availability model (SAM) was created for the Type 23 Frigate which predicts the number of onboard spares per mission and the length of time to repair equipment. No specific programme was developed for life-cycle costing (LCC) in the formative days of the Type 23 design but the LCC considered by YSL included:

a. design, manufacturing and production costs.
b. on board and base spares.
c. maintenance – scheduled and unscheduled.
d. training, fueling and heating.
e. refit.
f. equipment costs.

J W Harrison (Three Quays Marine Services) To what extent was isochronous governing for the diesel generators considered, and why was droop governing selected in preference?

D R Wilkinson & J D McIver (Yarrow Shipbuilders Ltd)

1. The CTF provided an ideal opportunity to evaluate the diesel generator speed and voltage droops in the system in which they would be operating and various settings from isochronous to 6% droop were evaluated. In the event, the ramp rates of the propulsion converters were quite modest and an isochronous setting would have been acceptable, but a complication occurred because the ship's service 600/450 V, 945 kW motor generator is driven by a squirrel-cage induction motor. So to produce a 450 V supply complying with the requirements of Def Stan 61-5 power supply characteristics in HM ships, frequency feedback from the 440 V system to MEPS is necessary to set the correct diesel generator speed (taking into account the motor generator motor slip). In effect, the equivalent of an isochronous system results but the actual speed setting is continuously varied.
2. Direct on-line starting of a 945 kW motor generator set on two or more 1.3 MW diesel generators in parallel demands at least a 4% droop to avoid unequal transient load sharing.

K H Aitken & J F Mykura (YARD) The author is to be congratulated on a concise paper which draws together the simulation, shore test and basin trial aspects of the Type 23 propulsion plant design. While it is perhaps inevitable that a paper covering such a wide subject should lack detail in certain areas, some amplification of the overall ship simulation modelling may be beneficial.

Yard were closely involved with the overall ship simulation from the early stages of Type 23 propulsion system design. The overall simulation model was developed largely by YARD from data supplied by manufacturers, and included models of the gas turbine, gearbox, SSS clutch, transient brake, propulsion motor, regulator and converter, shafting, propeller and hull. The diesel engine and generator are also modelled in detail, as are the motor generator sets. All the MEPS and MCAS control functions relevant to the propulsion system are simulated accurately.

In addition to the steady state performance, changeover sequences and brake wheel investigations mentioned by the author, the bulk of the simulation study comprised the transient analysis of manoeuvring performance in the normal drive modes. This work was used to:

1. examine the integration of the various control systems (MEPS, MCAS, propulsion motor) which had previously only been modelled individually;
2. examine performance in gas turbine and CODLAG drive which could not be covered by the CTF;
3. verify overall ship and machinery performance using the latest 'as built' data and, where necessary, define revised control system settings to overcome problems.

The simulation model was validated by comparing the results both with manufacturers' data and with results obtained from the CTF. In particular, motor generator starting performance and electrical system failures were compared with CTF results. Satisfactory agreement was achieved, and in some cases the simulation work was able to assist with the interpretation of the CTF results.

In terms of specific comments on the simulation results presented in the paper, in Fig 8 the operation of the gas turbine transient brake should be noted, as seen in the initial reduction of gas turbine speed. This operation would be controlled automatically by the MCAS system. The simulation of manoeuvres such as this allowed the effects of control system delays, timeouts and failures to be investigated and brake duty to be verified.

D R Wilkinson & J D McIver (Yarrow Shipbuilders Ltd)

1. At the outset of the presentation, the authors stated that they offered this paper with a feeling of humility as they were attempting to report on the integrated work of very many people, and it was acknowledged that the Yard work represented the climax of all the contributions.
2. A small working party known as the Propulsion Monitoring Working Group (PIMWIG) controlled this work and issued various reports. The authors confirm that the predictions made in these reports are aboard *HMS Norfolk* and are in regular use to ensure a complete understanding of actual plant dynamics.
3. Funds permitting, the authors believe that the equipment and ship models created by PIMWIG ought to be updated to reflect actual ship performance thereby establishing a valuable predictive tool for the Batch 1 design and a means of investigating new Batch 2 design problems.

J Neumann The author is to be congratulated on his courage in coming forward with this paper at a time when the sea trials of the Type 23 are about to take place. It is of course the sea trials which will provide the real validation of the design!

I found it impossible to distinguish with any confidence the various lines shown in Fig 1 of the paper and in the various graphs of the simulated manoeuvres.

The author refers to a shaft brake and a transient brake. Are these two different brakes, and if so what are their duties? It is stated that, in the crash stop from full ahead, the SSS clutch disengages either during deceleration or with transient brake assistance when the power turbine reaches idle fuel conditions. It would be interesting to know what it is that determines the choice, and what the results were of the simulations in this respect. In the rapid acceleration from stop the SSS clutch is referred to as being initially locked out with the gas turbine idling: presumably there is an interlock to prevent CODLAG being selected before the shaft speed has risen above the speed corresponding to power turbine idle?

In respect of the shore test facility, would the author please enlarge on his statement that all simulations in terms of hull and propeller characteristics were derived from shaft speed? How confident is the author in the correctness of his estimates of the transient hull and propeller behaviour, and on what does he base this confidence? The manoeuvring tests are stated to include stop to full ahead, and manoeuvres under heavy sea state conditions: was a gas turbine fitted to provide the full power? And how were the sea state effects built in?

It was interesting to read of the use of brake wheels during basin trials to permit the machinery to operate at maximum power. How far removed was this from full power? Will the author please also say something about the results of these basin trials and the use to which they have been or will be put?

D R Wilkinson & J D McIver (Yarrow Shipbuilders Ltd)

1. It is regretted that information regarding timescales is classified and cannot be included.
2. With regard to the brakes referred to, each shaft line has two brakes, the first is a large disc brake mounted directly on the propeller shafts, the primary purpose of which is to hold the shaft at rest as a parking brake. It is not intended that this brake should take any part in ship manoeuvring, rather it is intended to hold the shaft stationary in a tideway or in single shaft operation, but it can be manually applied at low shaft speeds if required. The transient brake is part of the main reduction gearbox and runs at intermediate shaft speed. It is controlled by MCAS to ensure that adequate differential torque is produced for operation of the SSS clutch during manoeuvres.
3. If during CODLAG–electric motor changeovers the SSS clutch fails to disengage and lockout by the time the SM1A has reached idle fuel condition, and the power turbine has reduced to an equivalent shaft speed of less than 90 rev/min, the control system applies the transient brake for a limited period (15 s max) to assist clutch disengagement .

   If the SSS clutch fails to disengage and lockout before the transient brake times out, an SSS lockout over-ride facility is available for emergency use to revert to electric motor drive conditions with the SSS clutch not necessarily in the locked out condition.
4. Regarding rapid acceleration from stop, with the power demand lever (PDL) at zero and the gas turbine at idle, as soon as the PDL is out of dead band, the electric motor accelerates the propeller shaft in accordance with the electric motor schedule until such time as the attained shaft speed is above equivalent PT off-load idling speed (approx 75 shaft rev/min). At this point CODLAG is manually selected.

   The gas turbine accelerates under changeover rate control with the SSS clutch pawls engaged until the relative speeds at the input and output elements of the clutch are matched when full SSS clutch engagement is achieved. Thereafter, normal acceleration schedules apply and the effect in terms of ship acceleration is quite spectacular.
5. The steady state and dynamic hull and propeller characteristics were reflected in shaft speeds and torques which the electric propulsion system had to meet. The authors have to agree with Mr Neumann's implication that the transient behaviour of a new hull and a new fixed pitch propeller is not a simple matter. The PIMWIG referred to earlier corporately analysed available data and agreed with what seemed to be the best predictions. This set the performance of the hull simulator. Sea trial results will produce some interesting data for comparison.
6. The reference to tests from stop to full ahead refers to full ahead electric motor drive. The presence of a gas turbine was not an option at the CTF.
7. Heavy sea state effects were introduced by applying a sinusoidal input to the electromagnetic brake, the periodicity of which was varied.
8. The brake wheels enabled the propulsion system to be run in all régimes up to 70% power, the absolute value achieved being less important than the ability to investigate and achieve a high degree of plant optimisation before the ship had left the quayside. For future ships the characteristics of the brake wheels will be adjusted to align with results obtained from contractors' sea trials.
9. On the practical side, the results of basin trials will be fed back to follow-on ships with an overall aim of reducing the plant setting to work time, particularly contractors' sea trials. The data should also be used to advance general knowledge in this area to ensure that the highly competitive warship export market is tackled in the most cost-effective manner.