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# MICROCOMPUTER-BASED SIMULATION OF MARINE PROPULSION SYSTEMS

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# Microcomputer-based Simulation of Marine Propulsion Systems

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## SYNOPSIS

*The paper is based on a case study in which a simulation of the propulsion plant for a CODOG frigate was established with the objective of defining appropriate control system specifications. The method of modelling, programming and experimenting with the simulation is described, with an emphasis on the diesel engine propulsion mode. The paper also addresses the potential impact of recent developments in microcomputer hardware technology and dynamic simulation software packages. Results obtained using a traditional hybrid computer implementation are directly compared with those obtained using a popular simulation package running on a desktop microcomputer. It is concluded that advances in these technologies presents an opportunity for extended application of simulation methodology.*

## INTRODUCTION

The application of simulation technology to the design of ship propulsion systems is now well established, and has in some sections of the industry been routine practice for several years.<sup>1-6</sup> The technique is more commonly associated with warship developments than with the merchant ship sector, although there are obviously exceptions to this rule.

In common with the more traditional mathematical techniques commonly associated with engineering analysis, computer-based simulation is concerned with representing physical systems or concepts by mathematical abstractions, with the ultimate objective of achieving improved understanding of the real system. In the particular context of marine propulsion plant, as discussed in this paper, the primary concern is the dynamic behaviour of the total propulsion system. This, in turn, is closely associated with the complex interactions which can occur between the respective machinery components, especially at off-design transient conditions which occur for example during ship manoeuvring.

The requirement to develop and implement this particular type of mathematical model usually arises when considering the design and evaluation of control systems for propulsion plant. Essentially, the computer simulation model is configured to represent the actual ship and its propulsion machinery when operating both under steady-state conditions (ie steady demand levels and constant speed) and under transient conditions (manoeuvring). Experiments with various control system philosophies can then be conducted at the design stage, under relatively controlled laboratory conditions; an approach which potentially compares very favourably with the alternative strategy of experimenting with the real system during the often strenuous circumstances associated with the ship commissioning stage.

Changes to the simulated system and its controllers may be made relatively effortlessly, and the effects investigated immediately by repetitively running the model at different conditions until the optimal all-round result is attained. Usually a significantly improved understanding of the dynamic behaviour of the physical system develops during such an exercise, often resulting in the eradication of potential problems at the earliest possible stage.

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It is probably true that the technology of simulation has traditionally been seen as something of a specialist activity, usually employed by control system consultants rather than the marine engineer. To some extent this situation has arisen because of the specific skills which have been required to implement computer simulations on the purpose-orientated analogue and hybrid computers which traditionally constituted the simulationist's and control engineer's workstations. Hardware costs associated with this specialist technology have also inevitably been very high and this has been another limiting factor.

Developments in the field of digital computers have, over the years, resulted in a gradual decline in the use of analogue type parallel processing devices. Consequently, simulationists concerned with a wide variety of engineering plant, ranging from the chemical process industries to aerospace, and the mechanical engineering and marine industries have progressively moved towards digital computers to implement their models. Traditionally, these have been mainframe installations, often using general-purpose high-level scientific languages such as FORTRAN or purpose-designed languages such as CORAL, CSMP, ACSL etc. The use of sophisticated and specialised digital systems has also remained a notable feature of such simulation activities. Mini-computers have also been extensively applied in this area, as their power progressively increased.

Protagonists of both analogue and digital systems will, no doubt, continue to debate the virtues of the respective systems.

In many ways the hybrid computer combines the strengths of both alternatives, but the major constraint in this case is the cost and complexity associated with this sophisticated machine which can only be used for specific engineering tasks and is not necessarily configured for general day-to-day commercial processing.

However, recent developments in the field of microcomputers have now evolved to the stage where relatively powerful machines with fast arithmetic processing and large memory capacity are available at very modest cost.

Software technology has kept pace with these developments and, for relatively low investment, specialist packages are now available which render simulation much more 'user friendly' towards the practising engineer. Increasing attention is being focussed on applications for this technology.<sup>7,8</sup>

In this paper it is proposed to discuss specifically the implications of these recent developments, with respect to the marin engineer who is potentially interested in the overall dynamics and performance of propulsion machinery. The objectives of the paper can be defined in three inter-related phases. First, it is proposed to review the techniques typically used when generating mathematical representations suitable for computer implementation of marine propulsion system models. This will be introduced using a typical example based on a CODOG propulsion system for a fast frigate. Secondly, details will be provided in a comparative context illustrating the techniques of programming the same model using hybrid and microcomputer systems. Finally, a review and comparison of typical results will be presented describing the method of using the models and illustrating the value of the technique. This discussion will include a review of the relative qualities of the two computing systems.

## THE PROPULSION SYSTEM

The CODOG arrangement as typified by Fig. 1 is familiar and popular for naval installations. It combines the advantages of high-efficiency diesel engine propulsion for cruise rating with the extremely high power performance associated with sprint rating under gas turbine propulsion.

The advantages of CPP in this context are readily apparent and well documented<sup>9</sup> and the practice of operating the propulsion sets in either/or mode allows gear ratios to be selected which permit independent optimisation of propeller matching for both propulsion modes.

## General principles of propulsion system simulation modelling

Typically the use of simulation in the design of control systems for propulsion machinery arranged in the CODOG configuration will converge upon the following broad objectives:

1. Optimising the performance of the diesel-only operational mode with respect to achieving maximum utilisation of the machinery whilst ensuring optimal overall vessel response in manoeuvring. Axiomatically this implies avoiding any operational constraints associated with the individual components comprising the propulsion system.
2. Achievement of similar specifications for the gas turbine propulsion mode.
3. Ensuring smooth, efficient and reliable power transfer between propulsion modes.

It is usual to model the system for straight-in-line ahead motion of the vessel. For twin-shaft systems (virtually mandatory for most naval installations) symmetry of machinery arrangement may often be assumed, so that only one line of propulsion machinery needs to be considered, this process being colloquially termed 'half ship simulation'. However, it is possible that in some cases 'handling' of the propulsion systems may produce significant differences in mathematical representation. In order to maintain reasonable fidelity it may then prove necessary to model both machinery installations simultaneously.

The systems approach to representing such an arrangement entails subdividing the complete plant into a sequence of subsystem blocks, which are then represented in terms of inputs (independent variables), outputs (dependent variables) and fixed data parameters.

Some of the subsystem models are common to all three operational modes, for example, the propeller and hull equations; others, for example the diesel engine or the gas turbine, may remain local to one particular operational mode only. Having characterised the subsystem models, full simulation is then implemented by synthesising the models of the respective parts and then solving all the differential, arithmetic and logical equations simultaneously and repetitively.

The overall philosophy of the model is illustrated in its simplest form by Fig. 2, which shows the interactions between the alternative prime movers, their control systems, the propeller and the hull.

Also shown in Fig. 2 is the nomenclature used in this and the other schematic diagrams.

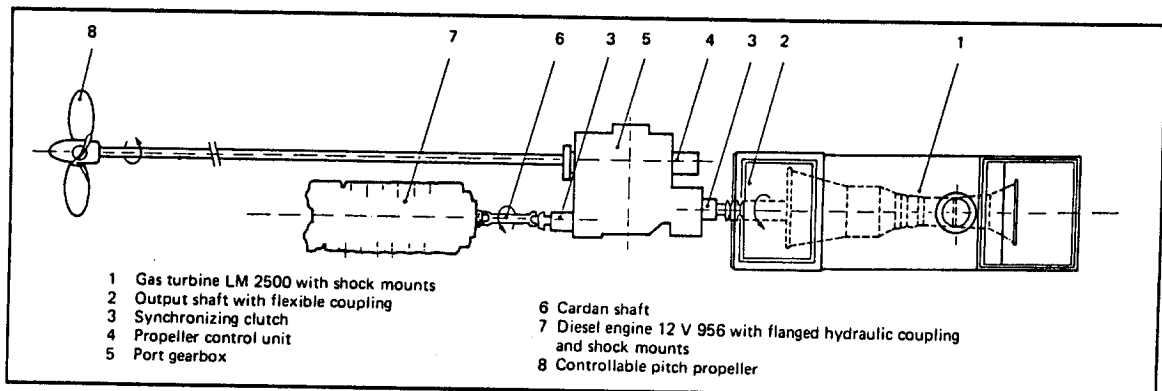


FIG. 1: CODOG arrangement (half ship)

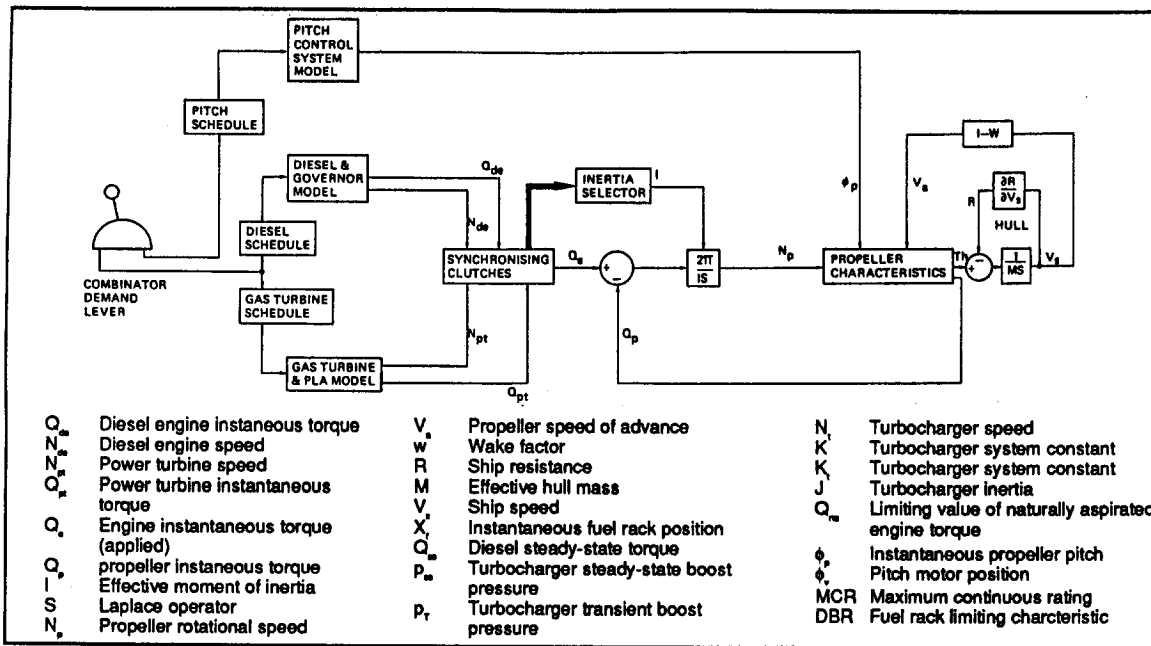


FIG. 2: Schematic diagram of overall system block diagram

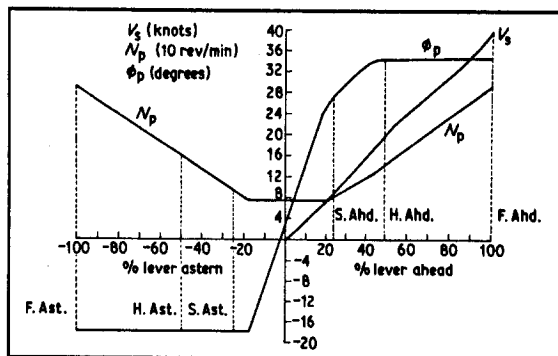


FIG. 3: Combinator schedules

### Diesel engine propulsion mode

The diesel propulsion mode comprises a twin-engine, twin-shaft arrangement with uni-directional variable speed, four-stroke engines developing a maximum 2060 kW per shaft at a speed of 1485 rev/min. The engines are fitted with mechanical/hydraulic governors incorporating a fuel rack limiting feature to constrain the available operational envelope.

Each engine drives through an oil-filled hydraulic coupling onto a single reduction gearbox of ratio 10.4:1. A hydraulic pump drive for the controllable pitch-propeller is also taken directly from the gearbox.

Engagement of the engine drive is via an overriding clutch which ensures automatic engagement when synchronism between input and output shafts is attained. Similarly, the clutch will disengage automatically if the input shaft speed falls below the output shaft speed. Since this option is only required during changeover modes, a control feature is included to prevent disengagement occurring during the power reversal phase which is normally associated with certain manoeuvring conditions.

The gearbox output shaft drives a five-bladed controllable-pitch propeller with hub-mounted hydraulic actuator supplied with oil by concentric tubes from the oil distribution box. A standby electric pump is available, in addition to the gear driven pump, to supply hydraulic oil to the actuator.

The propulsion control system is activated under the command of a single lever 'combinator' type system on the bridge, which simultaneously sets demand signals for the pitch and shaft speed. Figure 3 illustrates the profiles of the demand schedules extending over both diesel (up to notch 43) and gas turbine propulsion modes for both ahead and astern conditions.

### Diesel engine modelling

Since the simulation was to be used essentially for evaluation of control systems philosophies, it was not considered necessary in this case to resort to detailed thermodynamic modelling of the engine. The technique used was, therefore, based on a simple quasi-steady-state look-up table approach using empirical test-bed data provided by the manufacturer. Steady-state engine developed torque is thereby derived from a three-dimensional function generation database with engine speed and fuel rack settings as inputs. The 'windmilling' regime (where the propeller motors the engine in the no-fuel condition) is also included in this representation.

Below 54% of rated torque it is assumed that the engine behaves virtually as if 'naturally aspirated' and demanded torque is instantly available in response to fuel rack changes. Above the 54% threshold, air boost pressure conditions must be referenced before estimating dynamic engine torque. This necessitates invocation of a dynamic model of the turbocharger which is also based on a three-dimensional look-up table technique. The turbocharger dynamics are represented by a variable integration time constant which may be related physically to the rotor inertia and manifold packing lag effects. This time constant determines the speed of response of the rotor to changes in the supplied energy. Figure 4 illustrates schematically the computer implementation of this model providing

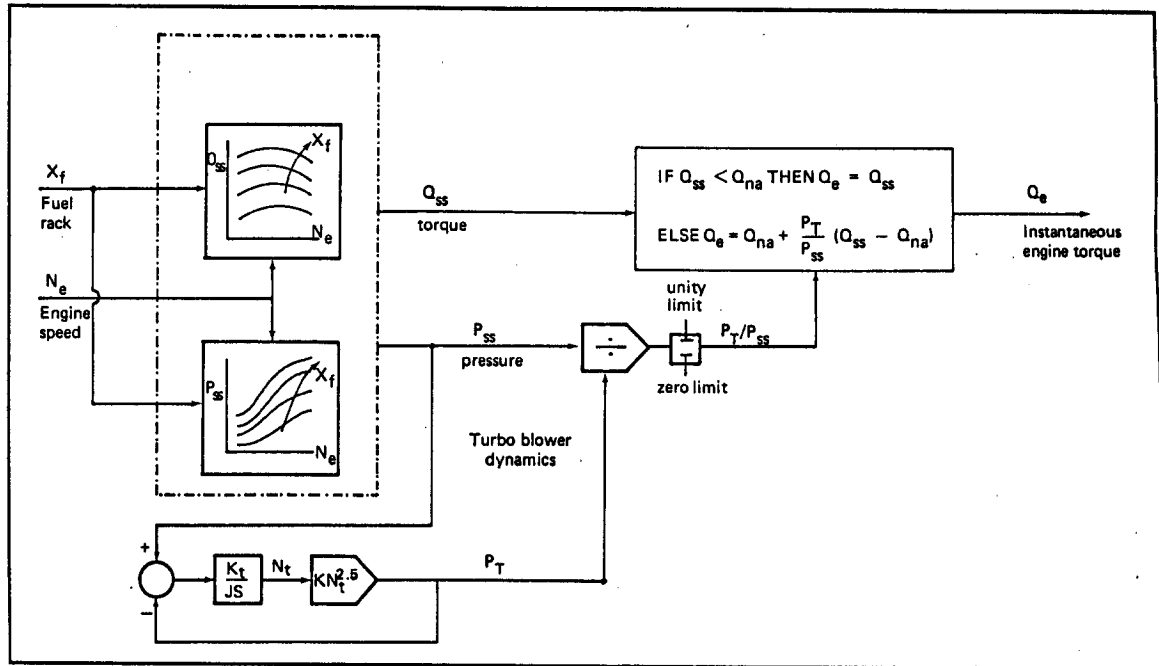


FIG. 4: Schematic diagram of diesel engine model

instantaneous engine torque as the primary subsystem output, in response to changes in fuel rack position and/or engine speed.

The shaft dynamics for the complete propulsion system are represented by a two-element 'lumped parameter' approach so that instantaneous engine acceleration is derived from the algebraic sum of instantaneous engine torque and load torque. The integration time constant is determined by the total rotational inertia of the system.

The load torque applied to the engine is provided as an output from the hydraulic coupling which is also modelled using a three-dimensional look-up table technique giving torque as a function of driver speed and slip.

#### Transmission and propeller system modelling

By combining the referred rotational inertias of all components downline of the hydraulic coupling runner, the second non-linear lumped parameter differential equation is established, in which instantaneous propeller speed is derived by integrating the algebraic sum of instantaneous driving torque and propeller load torque.

Discontinuities in applied torques and rotational inertias will occur during power changeover sequences, for example, as the clutches engage and disengage. However, for a defined propulsion mode, assuming clutches locked, the gearbox may be represented simply as a torque multiplier/speed reducer with allowances for losses which are functions of speed and load.

The propeller model, which is basically derived from the principles of dimensional analysis, is also represented by a look-up table database. Inputs are advance coefficient and propeller pitch angle; outputs are the thrust and torque coefficients. Instantaneous load torque and developed thrust are then computed from the conventional propeller equations.<sup>10</sup>

#### Propeller and hull interactions

Ship resistance, wake factor and thrust deduction factor are incorporated as empirical functions of ship speed. The in-line dynamics of the hull are then simply represented by a differential equation relating instantaneous net thrust to the total ship displacement, allowing for entrained water effects.

#### Gas turbine propulsion mode

The gas turbines employed in this particular installation were GE LM2500 units, each developing a maximum of 19.5 MW at 3600 rev/min. The on-engine control system allows the gas generator to perform within a permitted operational envelope with built-in acceleration/deceleration, overspeed and torque limiting features to ensure satisfactory steady state and transient performance under power scheduling operation.

Modelling of the gas turbine is required to characterise the instantaneous power turbine torque for given propeller shaft speed and power level actuator (PLA) position. Intermediate state variables include fuel flowrate, gas generator speed and gas generator discharge pressure.

The method of representing a non-linear gas turbine model valid for small increments in engine variables relative to defined steady-state base values is well documented.<sup>11,12</sup> Essentially, the engine is represented by a database containing a series of partial derivatives and steady-state baseline values set up as functions of the independent variables fuel flowrate and gas generator speed. This empirical approach is ultimately based on manufacturers' data derived from test-bed trials.

In the present context, this modelling philosophy was adopted using a slightly simplified version of a model provided by the gas turbine manufacturer. Standardised conditions for atmospheric temperature and pressure were used with fixed values for induction and exhaust trunking losses. Dynamics of the power train were represented by a single lump model of the

rotating parts from the power turbine through to the propeller with the various inertias being referred through the appropriate gear ratio corresponding to the gas turbine operational mode.

### Control systems

Certain aspects of the propulsion control system's philosophy were already partially defined by installation specification received at the outset of the modelling process. Transmission of control signals from the bridge control unit to the set point of the diesel engine governor and gas turbine PLA system was implemented with specified rate limiters for both acceleration and deceleration of the respective units. The diesel engine droop governor characteristic was specified by the manufacturer and a simple single-order lag of time constant 0.2 s was used to describe the dynamics of the hydraulic fuel rack actuator.

A schematic diagram of the pitch control system which had been previously specified for this particular system is illustrated in Fig. 5. The hydraulic pitch servo responds to movements of a pilot valve which, in turn, is positioned by a direct current electric pitch motor driving a lead-screw. The bi-directional pitch motor is switched and driven at constant speed under the control of an electronic pitch motor integrator, with controller locking logic and imposed hysteresis to prevent the motor output position  $\theta$ , running on beyond the achieved pitch  $\theta_p$ . The maximum discharge rate of the hydraulic pumps effectively limits the maximum pitch rate to 2.3°/s, which implies that the system behaves as a pure integrator for large pitch errors but responds as a single-order lag for small errors.

A significant objective of the simulation study was to evaluate various load control strategies incorporating this particular pitch control mechanism with the existing diesel engine governor and gas turbine fuel control systems. To this

purpose, additional logic signals, capable of locking and, if necessary, reversing pitch direction, were also to be incorporated, as required.

An additional requirement of the control system specification was to implement isochronous outer speed control loops referenced to propeller shaft speed for both the diesel engine and gas turbine modes. These control loops were initially designed using conventional frequency response techniques based on linear analysis, with large signal 'non-linear' performance being evaluated by trial during subsequent testing using the simulation model.

### SIMULATION IMPLEMENTATION

A complete simulation investigation of all significant propulsion modes was originally investigated using a hybrid computer facility. This included the gas turbine and changeover modes in addition to the diesel propulsion mode. Typically, the digital facility of the computer was used for look-up table databases and logical processing, while the analogue was used for integration, controller implementation and parallel logic processing. Real-time processing was facilitated with continuous output and data recording using an 8 channel analogue pen recorder.

At the present time, the microcomputer implementation has been confined to the diesel propulsion mode only. This exercise was conducted principally as a method of assessing by comparison the capabilities of the microcomputer and its associated software package.

However, for completeness, it is ultimately intended at some stage in the future to extend the exercise to evaluate the other operational modes.

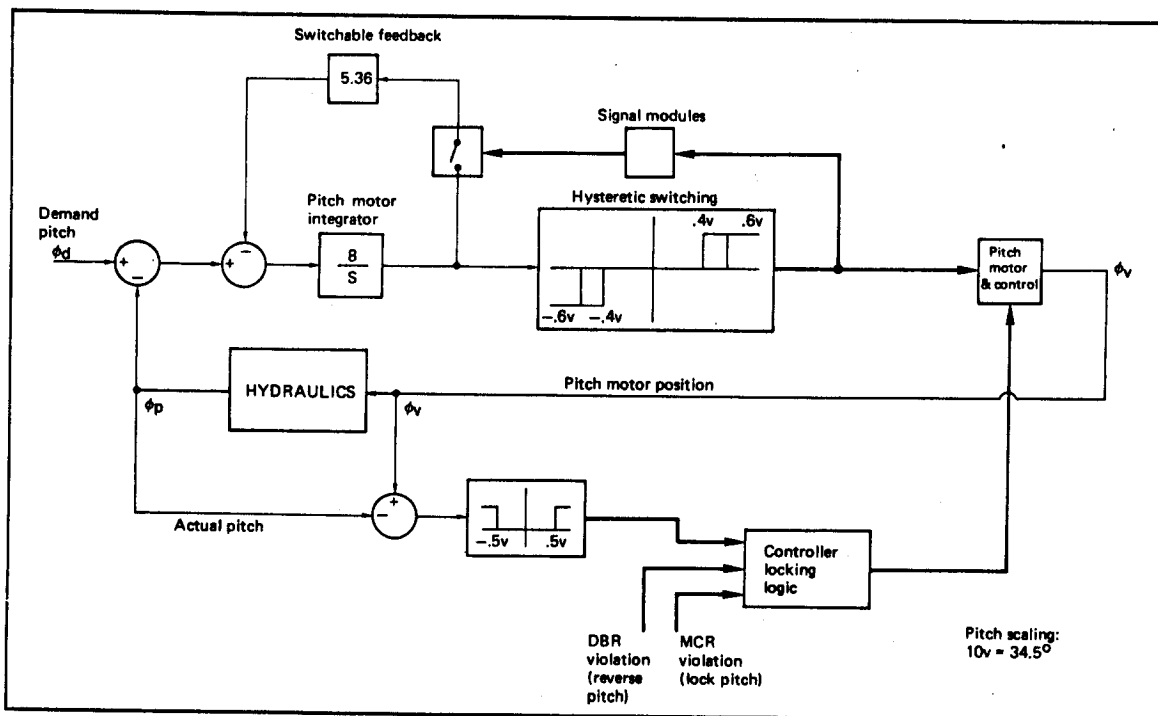


FIG. 5: Schematic diagram of pitch control system

## The microcomputer simulation package

The original hybrid computer implementation had been developed with the specific objective of attaining real-time simulation and data recording (this being one of the key advantages of the hybrid system). Consequently, the coding had been written to minimise computing time with the result that many variables did not appear explicitly as system outputs.

When programming the digital microcomputer version of the model using the ACSL simulation package (Advanced Continuous Simulation Language) this philosophy was abandoned and no attempt was made to attain real-time operation. Consequently, run-time data were more copiously available. However, a significant reduction in computational speed was originally encountered, typically extending computational runs to ten times real time.

By making relatively minor simplifications in the model it was possible to remove certain elements having very small time constants whose overall influence on the system was considered to be negligible. Consequently, integration step time was reduced (ie step size was increased) with the result that the model was seen to execute in typically three times real time.

The ACSL simulation package splits the programming effort into two distinct phases. The model coding is written in a relatively user-friendly high-level language reminiscent of FORTRAN. However, the language is configured so that all the common facilities traditionally used in dynamic simulations such as lags, time delays, hysteresis, function generation and various integration algorithms are conveniently available using simple commands. Equations need not be sequentially sorted by the simulationist since this feature is handled by the software. Additional FORTRAN subroutines and ACSL MACROS may also be loaded, if required, and the entire program is then 'translated' by the ACSL software into FORTRAN code. The FORTRAN version is subsequently compiled and linked to produce an executable machine language file.

Flexible 'exercising' of the model is facilitated by a separate set-up and command 'RUN TIME' driver program which is configured to allow convenient changes of model parameters, run lengths, output data format, and plotting details. Facilities are provided for performing and then storing, on file, results from steady-state analysis. Dynamic data can also be stored on separate files during successive runs, then called back at a later time for plotting, etc.

A schematic representation summarising the computational 'architecture' is illustrated in Fig. 6.

The overall approach to modelling and 'exercising' the system is, therefore, very similar to that which would be followed by an analogue or hybrid simulationist. Further details of the package and examples of its applications are well documented.<sup>13,14</sup>

### Steady-state results

The simulation was primarily developed to study transient behaviour of the system, but it also provides a flexible structure in which to characterise steady-state performance of various propulsion plant components.

By setting the combinator lever to a particular demanded position and allowing the transients to subside, it is possible to attain steady-state data which can then be presented in convenient tabular format on VDU or printer. Alternatively, several steady-state points can be connected up to form characteristics of, for example, engine torque, speed, specific fuel consumption, propeller efficiency and ship speed, all plotted against a

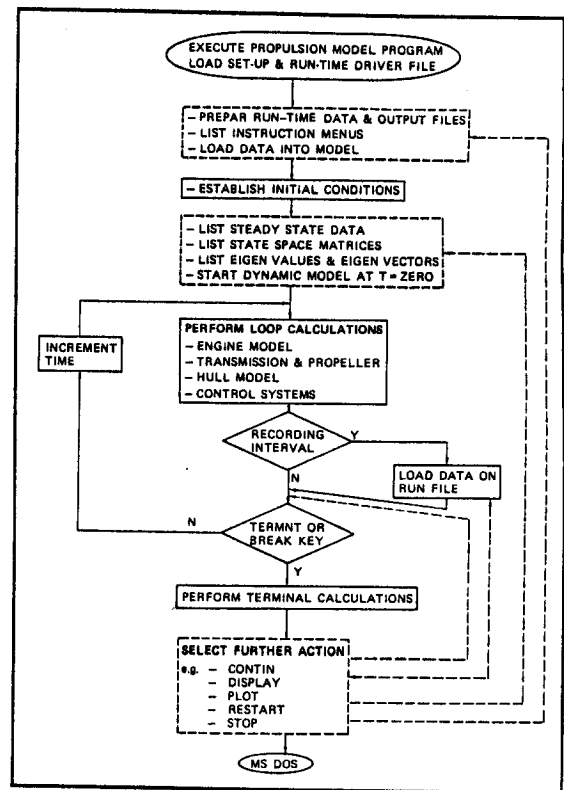


FIG. 6: Schematic diagram of microcomputer programming structure

common base of combinator lever position or shaft speed. This technique potentially provides a useful facility for fine tuning of the combinator schedules if, for example, it is required to improve overall system efficiency across the operating range by optimising the relationship between propeller pitch and rotational speed.

During commissioning of the microcomputer model a detailed comparison of results was made with the original hybrid computer data and excellent correlation observed throughout.

### Transient results

Obviously the scope for system investigation using simulation is extremely wide, but as a typical illustration it is proposed to use the relatively common example of the load control problem to demonstrate a typical application. An important aspect of the simulation exercise is that it provides the analyst or investigator with a powerful tool for predicting and understanding in detail the potentially elusive behaviour often associated with dynamic performance of highly non-linear interactive engineering systems.

Careful analysis of recorded data can yield a profound and detailed account of events which could otherwise go unnoticed or misinterpreted.

To provide an illustration of the use of this approach, a limited number of selected recordings is presented for discussion. An overview of the salient features is given in the main text with further, more detailed, analysis being submitted in Appendix 1. The results presented all refer to the diesel propulsion mode with manoeuvres referenced to the limit of the engine's capability (maximum combinator position 43).

*Stop – full-ahead manoeuvre*

Figure 7 illustrates a typical sequence of events which can occur under the control of a simple combinator scheduling system when the bridge control lever is moved from the stop to full-ahead position with the objective of achieving maximum vessel acceleration. The demanded engine speed ( $N_d$ ) is seen to ramp steadily upwards at the specified rate under the action of the rate limiter which effectively converts a step change at the control lever to a ramp input at the engine governor set point.

Similarly, the pitch actuator ( $\phi$ ) ramps at its maximum rate towards the new demanded value.

However, the achieved engine speed ( $N_e$ ) does not follow the demanded speed time locus throughout the transient as is

clearly evident. In fact, a partial stalling of the engine results and recovery occurs only slowly as the transient proceeds. Clearly this is an unsatisfactory outcome illustrating that, although suitable for defining steady-state performance of the plant, a simple combinator-based strategy does not, in itself, provide adequate transient performance.

The result shown in Fig. 7 has been redrawn from recordings obtained from the simulation results. Reproductions of the original output are presented as Fig. A2.1 in Appendix 2 to illustrate the form of the recordings obtained from the hybrid and micro computer systems. This also shows the excellent correlation existing between the results obtained from the two alternative systems.

The load acceptance performance of the installation was

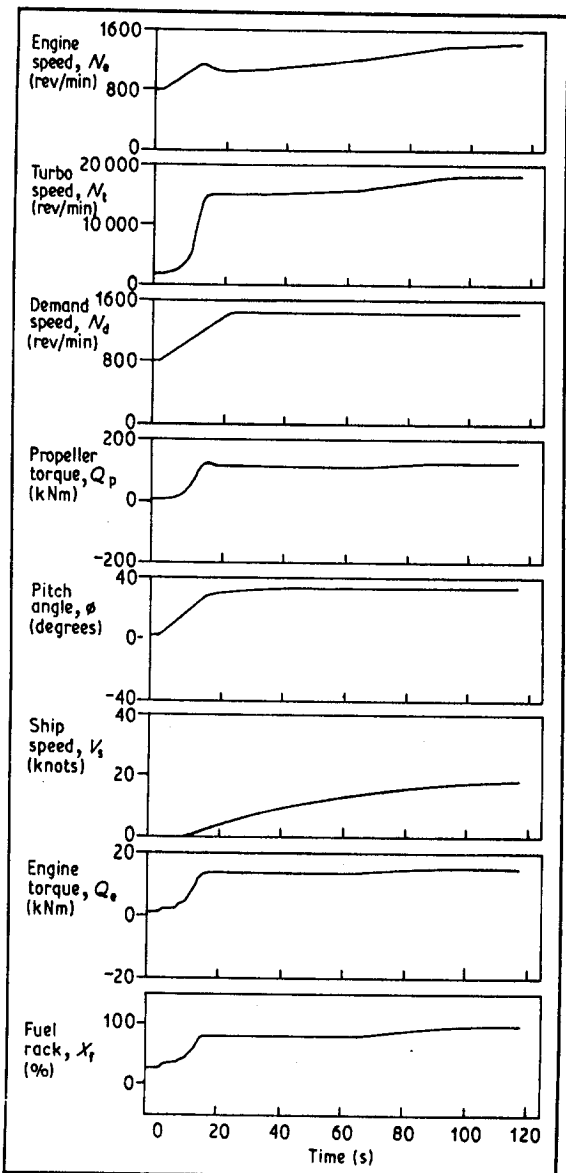


FIG. 7: Crash – full-ahead manoeuvre without load control

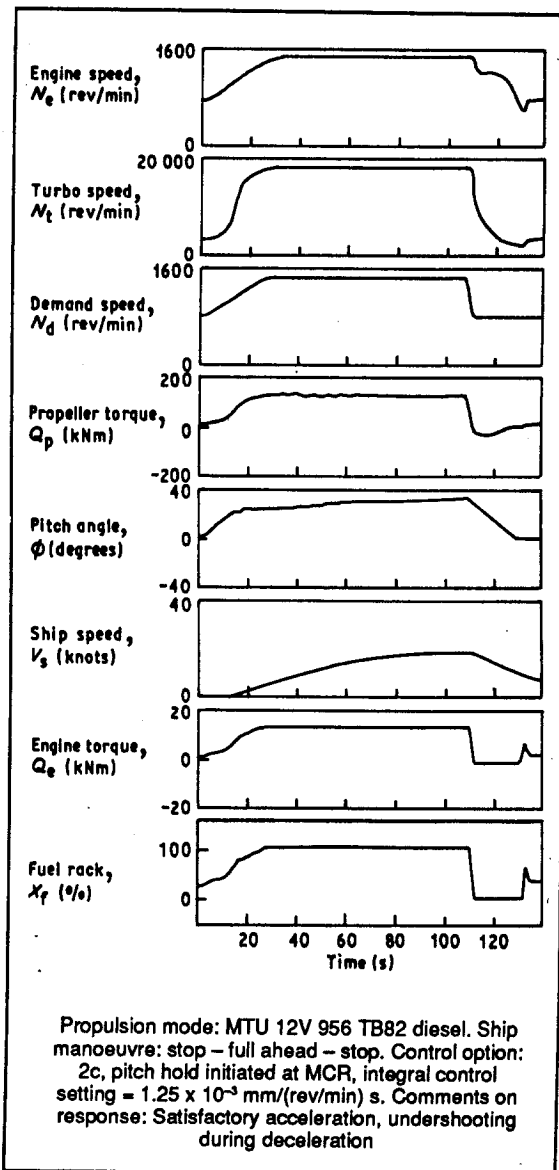


FIG. 8: Crash – full-ahead and stop with load control

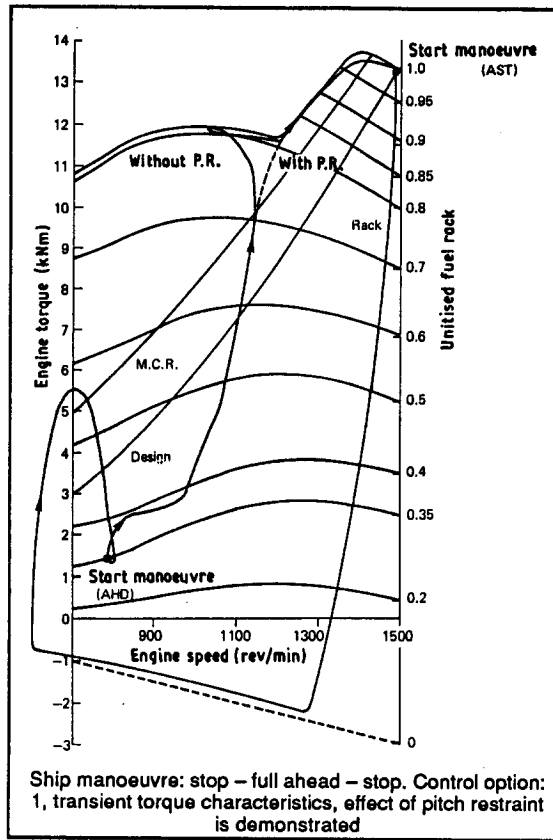


FIG. 9: Torque/speed plane representation of transients

subsequently improved by designing a suitable load control system. For practical implementation this system must obviously be compatible with the existing hardware, as previously illustrated in Fig. 5. The strategy adopted was to introduce a feature whereby the load controller compares the engine fuel rack position ( $X_f$ ) with a reference characteristic established by an electronic function generator and locks the pitch if the reference is exceeded.

The simulation was used to predict the optimum setting of the reference characteristic so that the engine could be utilised to maximum capacity during the transient without violating any of the constraints associated with the operational envelope. The result of the modification is to produce the transient result shown in Fig. 8, which shows the achieved engine speed ( $N_e$ ) following closely the demand value ( $N_d$ ) throughout the acceleration transient, subsequently attaining maximum shaft speed in the fastest possible time. The pitch ( $\phi$ ) is seen to be initially held at an appropriate level to facilitate this modified response and is gradually released upwards, only as the vessel speed ( $V_s$ ) increases, thereby reducing the propeller load torque at the corresponding shaft speed. The relatively unproblematic (although unoptimised) load rejection transient is also shown in Fig. 8 and it is of interest to note typical events during this manoeuvre, following the decrease in demand pitch and shaft speed. The turbocharger shaft speed ( $N_t$ ), instantaneous propeller torque ( $Q_p$ ) and instantaneous engine torque ( $Q_e$ ) are also recorded during these transients.

An alternative perspective of the transients referenced

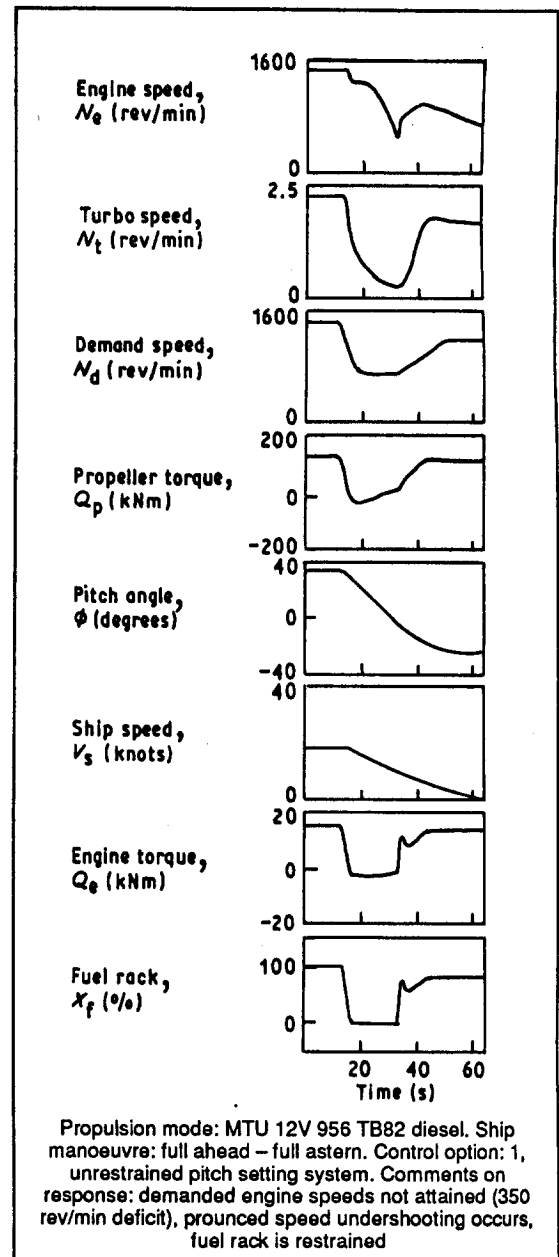


FIG.10: Crash - stop manoeuvre without load control

above is reproduced (Fig. 9) as a torque/speed plane ( $Q_e/N_e$ ) representation. This format provides a particularly useful comparison between the transient load lines obtained when accelerating the system before and after implementing the load controller. In the former case, the engine is clearly seen to be driven into a semi-stall regime as the governor torque limit intercedes to prevent overfueelling of the engine in the lower speed range.

Following the initial acceleration phase, speed falls to 1020 rev/min with torque 11.7 kNm before re-acceleration eventually occurs along the fuel rack limit characteristic. Conversely,

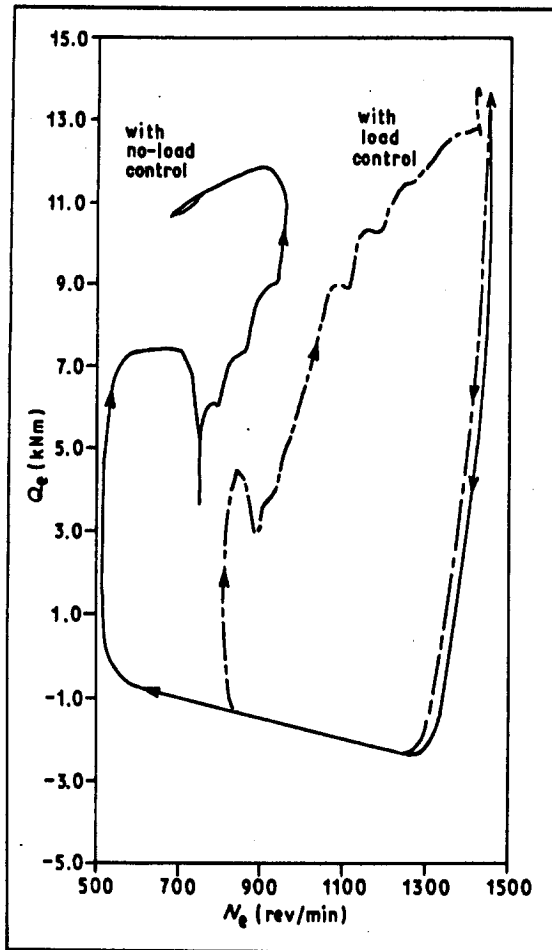


FIG.11: Effect of load control on crash - stop manoeuvre

under the action of the pitch locking load control system, it is apparent that a much improved transient situation is achieved, following the trends already identified in Fig. 8.

#### Crash-stop manoeuvre — full ahead to full astern

Achieving satisfactory acceleration transients does not necessarily ensure adequate performance when attempting crash full-ahead to full-astern manoeuvring. Figure 10 is reproduced from the hybrid simulation results and illustrates events observed with an unrestrained pitch setting system.

The discrepancy between demanded and achieved engine speed is particularly evident during this manoeuvre and the engine is clearly being driven towards the stall condition. A detailed account of events is again given in Appendix 1, together with a description of investigations leading to rectification of this behaviour.

Figure 11 shows in torque/speed plane format the response ultimately achieved by incorporating appropriate load control features with the objective of maximising ship deceleration and hence minimising ship 'reach'. The effect of implementing the modifications in the control strategy is readily apparent upon comparing the superimposition of the respective load line transients. The original version of Fig. 11, as produced directly

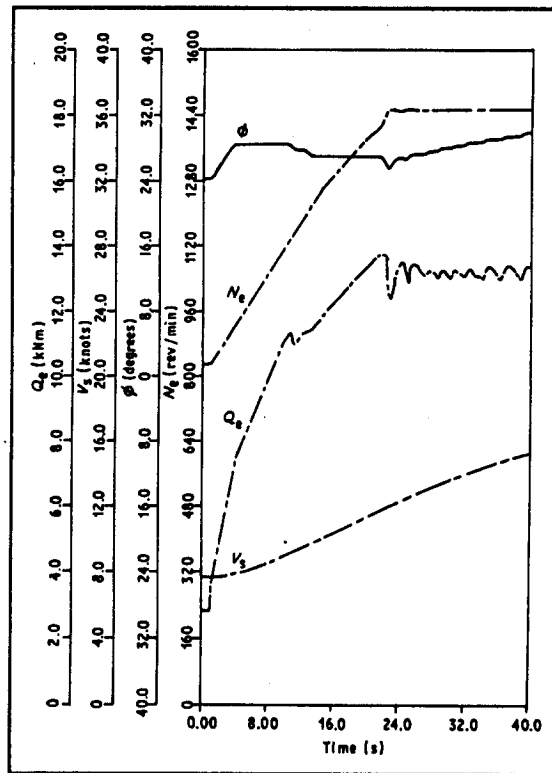


FIG.12: Half - full-ahead manoeuvre

by the microcomputer plotting software, is presented as Fig. A2.2 in Appendix 2.

#### Half-ahead - full-ahead manoeuvre

Having established acceptable behaviour of the system for the most severe operating transients, it might intuitively be considered that intermediate manoeuvring requirements would naturally prove unproblematic. However, it is good practice to use the simulation to evaluate fully all manoeuvring situations which can be envisaged in service. In this case it was found, in fact, that when attempting maximum acceleration during the half-ahead to full-ahead manoeuvre, a problem was encountered when relying on the pitch locking system as specified above.

It therefore became necessary to introduce an additional feature into the control system so that the pitch angle is not only locked as the fuel rack attains the MCR setting but also actually reduced if the fuel rack setting continues to rise towards, and eventually violates, the fuel rack limit characteristic. It was determined by experimentation that the pitch reversing feature was not desirable at higher speeds where the fuel rack limit is characteristically rising, and it was therefore only implemented over the constant section where engine speed is less than 1200 rev/min.

The results obtained are shown in the redrawn Fig. 12, which clearly shows the action of the pitch reversing feature. The plotting in this case has been formatted and reproduced directly in the line-plot mode to demonstrate this alternative facility of the ACSL software graphics package. The original version of Fig. 12 is presented for completeness as Fig. A2.3 in Appendix 2.

## CONCLUDING REMARKS

The paper has provided an insight into the techniques used in formulating mathematical representations of typical marine propulsion plant. The methodology of simulation and a typical application of the modelling process have been demonstrated by example in the context of performance optimisation associated with various control functions under the highly non-linear and interactive conditions which can occur during vessel manoeuvring. An attempt has been made to demonstrate how improved physical understanding of the system can be promoted and unexpected features can be identified and accounted for during design.

The thrust of the paper has also been directed towards demonstrating the feasibility of the microcomputer-based ACSL implementation of propulsion and control system simulation. In practice the microcomputer has proved to be extremely efficacious and the results obtained from the simulation model have been consistently identical with earlier versions obtained using the hybrid computing facility. Since the earlier results had been partially validated, where possible, with respect to selected subsystem empirical data, it appears reasonable to assume that the ACSL model results are reasonably valid also, although physical test results from onboard sea trials of the complete system were, unfortunately, unavailable on this occasion. The behaviour of machinery during transients before and after implementing load control is, however, clearly representative of typical documented experience.<sup>15</sup>

It is particularly interesting to note the quality and presentational flexibility of the graphics output obtained from the simulation package. The various graphical formats which are produced by the library plotting routines are conveniently configured and production is of report quality, as can be readily ascertained upon consideration of the examples presented in the paper. Also, it is considered from experience of using the system that the techniques of programming are significantly easier to assimilate than those associated with a hybrid computing system. Similarly, the language features are obviously configured to reduce programming effort compared with direct implementation in a general purpose language such as FORTRAN.

In the particular example presented in this paper, the simulation executed at a rate of approximately one-third real time, which implies conversely that total execution time is three times slower than real time. It should be noted, however, that no attempt was made to optimise the coding with a view to reducing the arithmetic and logical processing requirements and hence reduce execution time.

The machine used was a 16-bit IBM XT compatible personal computer fitted with an 8087 maths co-processor chip and an 8 MHz clock. It is considered that these options should

be considered virtually mandatory for microcomputer-based simulation work, since they significantly reduce execution time. The computer was also equipped with a 20 Mb hard disc, which again is considered mandatory, since in this case executable files were typically 360 kbytes in length, which implies obvious problems for floppy disc storage. High resolution graphics was also specified producing very acceptable screen plotting with an option for down-loading to a low-cost standard dot matrix printer for hard copy if required. It should be noted that the plotted data presented in the paper were produced by a more elaborate and expensive pen-plotter. However, it can be verified from experience that the dot matrix printer output is entirely adequate for many applications.

It will be appreciated that the rate at which technology is advancing in this area will inevitably produce further improvements in the near future. Initial investigation with an IBM AT compatible microcomputer suggests that execution time can be reduced by a factor of three for the test model used here, which effectively permits real-time operation, if required. The ACSL package itself is also subject to continuous updating to improve its performance and facilities, as are the competing software packages already existing or entering the market.

It is concluded from the 'benchmark' trials which have been implemented that the systems now available are quite adequate for implementing many aspects of practical simulation which a decade ago would have required considerably more elaborate machines and higher levels of operator familiarity than is currently required. However, it must be recognised that the model used in this case study is, by modern standards, relatively simple and for the many highly sophisticated real-time applications frequently experienced in industry, specialist facilities will continue to prove mandatory. It would therefore appear that the way is now clear for dynamic simulation techniques to be understood and utilised by an increasing number of practising engineers as a matter of routine, rather than speciality. By this process a relatively low-cost, but powerful, design tool and adaptable facilitator of understanding may provisionally be considered to have evolved into a state where multiple applications will be found in previously uncharted areas.

## ACKNOWLEDGEMENTS

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## APPENDIX 1

### Detailed analysis of recorded simulation transients

Figure 7 shows the response to a crash – full-ahead manoeuvre without the intervention of any load control system. As the demand speed increases the fuel rack is initially opened to a value of 37% and remains relatively constant for about five seconds as the propeller load torque increases relatively slowly for low values of speed and pitch. As the rate of torque absorption increases, the fuel rack opens wider until the governor fuel limit mechanism is initiated at 80% fuel rack. A continued increase in propeller pitch results in an increased load torque which cannot be supported by increased engine torque. The speed, therefore, falls until load torque becomes equal to engine torque, at a value of 1020 rev/min (a drop of 125 rev/min).

The effect on propeller thrust and hence ship speed is significant throughout this period, with the result that vessel performance is impaired. Subsequent recovery of the engine speed to its final steady-state value is eventually achieved as the ship speed increases, thereby reducing propeller load torque, due to the increase in advance coefficient.

It is evident that for a protracted period during this transient, the engine performance is restricted by the fuel rack limitation and full engine speed is not attained until two minutes after the initiation of the manoeuvre. Apart from the obvious degradation in vessel performance incurred by this restriction, the engine manufacturer's recommendations for engine operation are also violated, and in practice it is probable that heavy smoke would be emitted throughout such a manoeuvre.

During 'crash/stop' astern manoeuvres it is common practice to reduce the engine demand speed to idle throughout the period when pitch is being reduced. This feature is clearly shown in Fig. 10. The idle select period is followed by re-acceleration of the engine as the pitch begins to move into the astern mode. The so-called 'windmilling' phase is clearly visible during this manoeuvre. As the fuel rack moves to the shut-off position, the engine speed initially drops, but then increases slightly and is maintained at a higher value than is demanded due to the motoring torque being fed back from the propeller. As the pitch reduces, the windmilling torque also reduces and shaft speed drops correspondingly. A degree of undershooting is evident before the shaft speed again begins to rise, following the ramped demand speed signal which is initiated as soon as the pitch angle attains a negative value. Eventually, however, increasing astern pitch produces load increases which violate the engine fuel limit feature, and subsequently the engine speed actually drops before settling in a semi-stalled condition, which prevails until the end of the recorded transient.

Consideration of the torque/speed plane version of these events (Fig. 11) clearly reinforces the observations made above. In particular, a significant torque overshoot is evident as the governor brings on fuel following the 'power injection' or 'windmilling' phase of the transient. The second trace, shown in Fig. 11, shows the combined effect of raising the intermediate idle speed to 1000 rev/min, and introducing an effective load controller together with modified speed controller terms. Following the 'windmilling' phase engine speed is seen to

follow its demanded value with torque corresponding closely to the MCR throughout the transient. Full astern power is thereby achieved in a relatively short time in a smooth efficient manner.

It should be noted that the ship model is not valid for negative ship speeds since astern performance does not warrant detailed attention. The simulation is, therefore, programmed to terminate automatically as soon as zero ship speed is reached.

The problems with half to full-ahead manoeuvring were also mentioned in the main text. In this case fuel rack limitation was seen to occur and engine speed response subsequently was delayed over a period of approximately 50 seconds. Further consideration suggested that this situation arises since pitch is initially well advanced at the start of the manoeuvre, while engine rev/min is relatively low. The pitch locking system is actually activated quite early in the transient but as the engine speed is increased then the propeller speed, and correspondingly the applied load, increases rapidly also, with the result that the governor fuel limit is violated and the acceleration rate adversely affected.

The method of solution has been identified and Fig. 12 illustrates the results achieved by this modified strategy. An initial steep rise in engine torque results from the requirement to accelerate the rotating components and overcome increasing propeller torque. Pitch initially increases for approximately 2 s before the pitch lock feature intervenes. After 11 s the pitch reversing mechanism comes into play reducing pitch to permit the required engine acceleration. The pitch then begins to rise again 23 s into the transient and continues relatively smoothly until steady state is finally achieved.

## APPENDIX 2

### Raw data output from computer simulations

Figures A2.1-3 are provided as illustrations of typical direct simulation output. Hybrid computer results were obtained by continuous recording on an 8 channel analogue thermal plotter in strip chart form with original paper width approximately corresponding to A3 size. The axes and text shown on such figures must be typed on retrospectively. The microcomputer recordings reproduced here were originally plotted onto standard A4 size paper, although the facility also exists within the software to plot originals on A3 if required. ACSL plotting is not activated until the simulated run has been completed.

### Nomenclature used in microcomputer output figures

NE	Engine speed
NT	Turbocharger speed
ND	Engine demand speed
QP	Propeller torque
PA	Achieved propeller pitch
VS	Ship speed
QE	Engine torque
ZF	Fuel rack position

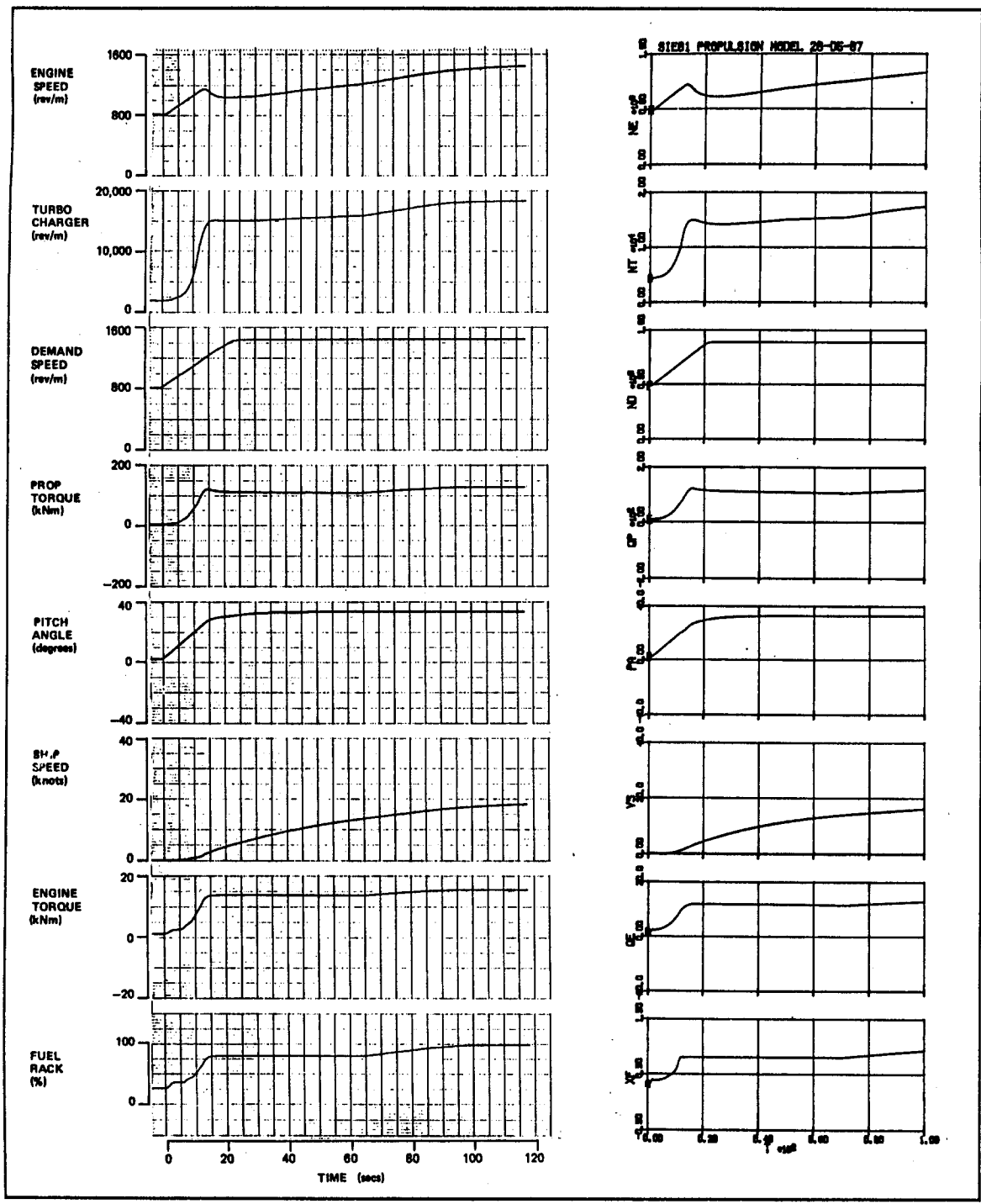


FIG. A2.1: Crash - full-ahead manoeuvre, Left, hybrid simulation; right, direct microcomputer strip chart recording

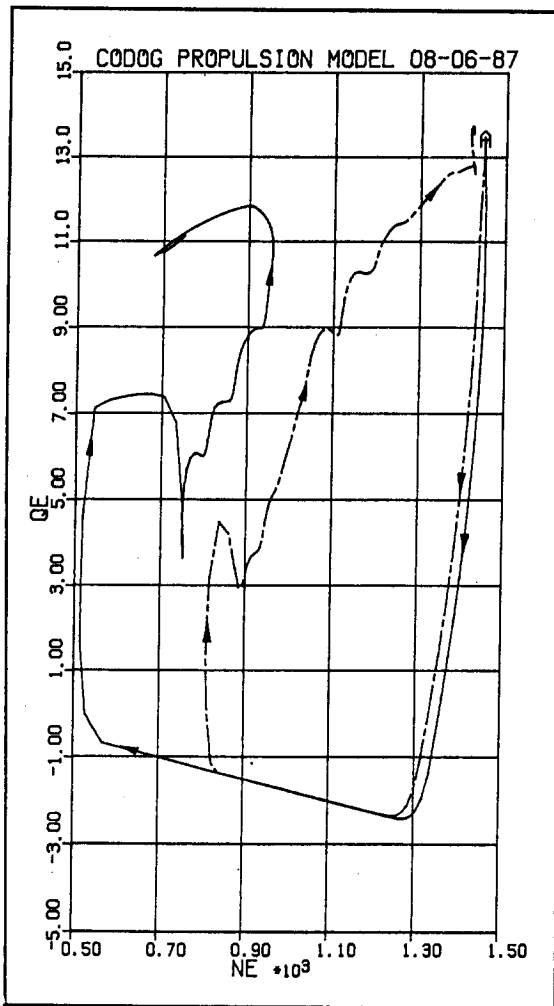


FIG. A2.2: Crash - stop manoeuvre, direct micro-computer torque/speed plane recording

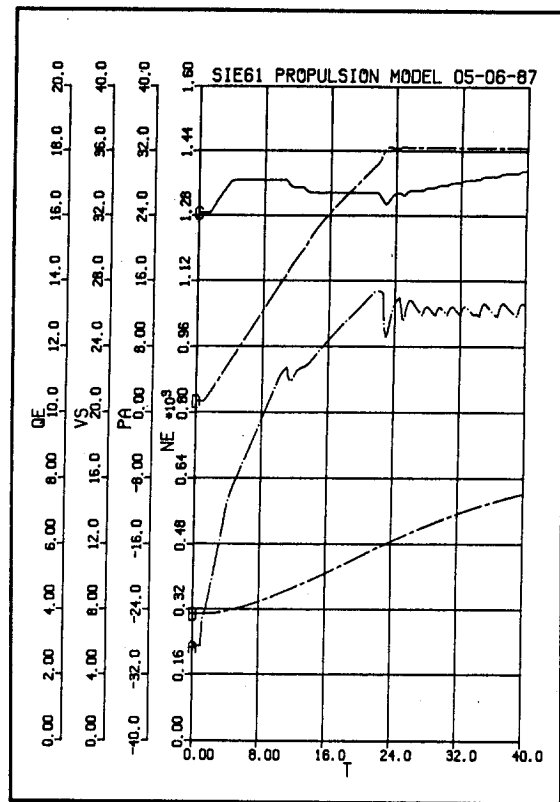


FIG. A2.3: Half - full-ahead manoeuvre, direct micro-computer line plot recording