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TRANSACTIONS (TM)

MODEL SIMULATION IN SYSTEM DESIGN AND TRAINING

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Paper 17

An Introduction to the Use of Model Simulation in System Design

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SYNOPSIS

This paper is intended to introduce mathematical modelling of marine systems to the non-specialist marine engineer and to give an appreciation of its uses and of some of the limits of application. Although different types of simulation are discussed, the paper concentrates on continuous non-linear modelling and shows, by example, how models are constructed and the sort of decisions which can be based upon the results.

INTRODUCTION

Simulation by mathematical models is a widely used method of analysing the behaviour of complex systems. This paper highlights the benefits which can accrue if these techniques are applied wisely.

Simulation can be considered as the process of formulating, implementing and using a mathematical representation (model) of a system to analyse its dynamic behaviour.

There are many systems to which simulation analysis has been applied and typical areas within the marine field are: propulsion systems, ship dynamics, structural dynamics, subsea engineering and operational research.

Within these areas simulation models can be used cost effectively to analyse and optimise system performance under a wide range of static and dynamic conditions. Some specific uses include: control-system design, machinery and ship performance assessment, equipment specification, failure analysis, protection-system design, operator training and transportation studies.

Models provide a vehicle for the engineer to experiment with design options and to establish that a particular system is capable of carrying out its required duty. The mathematical model also provides an effective focus on the interface between different plant items to ensure that the specification includes sufficient performance information and that all the interfacing systems will operate together effectively when delivered. Some surprising inconsistencies in the design data often come to light at the model stage of a simulation project before the analysis has even begun!

MATHEMATICAL MODELS

Simulation models can be categorised under two major headings: continuous and discrete. This paper concentrates on the use of continuous simulation models to investigate dynamic systems which can be represented by simultaneous differential equations with time as the independent variable. Discrete-event simulation is also of interest to marine engineers, for example, as used in the operational analysis of a tanker fleet. It is discussed later.

The type of models used tend to be determined by the nature of the system, purpose of the study, computing facilities or perhaps financial constraints. Continuous models could be linear, non-linear, real time, etc. For example, if control hardware or human interaction is to be included in a feedback loop with the simulation model, real-time operation is required. The level of detail is often determined by the purpose of the study.

For example, if the model is intended for plant design to determine basic parameters then it may be detailed and physically/theoretically based (eg, a model of a gas turbine with detailed theoretical thermodynamic relationships between components in the gas flow path).

On the other hand, if the model is part of a system for dynamic analysis then it may be possible to use a less complex but still fairly complete model, valid over the whole operating range (eg, the gas-turbine model could be based on non-linear empirical relationships and transfer functions of various components). This type of model could be used for the quantitative design of control functions for a complete system, such as a ship propulsion system.

Structure

A simulation model usually consists of a number of program modules, each representing a major component of the system. In general, program modules are initially of the theoretically based parameter type, developed from first principles. The use of suitable trial data may allow a simplification of this form of model to a transfer function type which, while retaining the essential model characteristics, requires less computational time and capacity.

Typically, a mathematical model of a ship propulsion system would be of the form shown in Fig. 1. Each major component of the system, such as the prime movers, gearboxes, etc., is represented by a program module. This modularity, apart from being good programming practice, affords the possibility of using previously validated modules in a new system model, with the attendant increase in confidence.

For example, most modern warships have gas-turbine propulsion engines which, themselves, are designed and built as units and which vary little from ship to ship. It is therefore quite easy to use a well proven mathematical model of such engines in new designs. Bearing in mind that the gas-turbine models are an appreciable proportion of the whole system, the engineer can then concentrate more effort on the remainder of the system.

Implementation

There are many ways that a mathematical simulation model can be implemented to run on a computer. Analogue computers have been, and continue to be, used with good effect. On such machines it is relatively easy to represent some of the

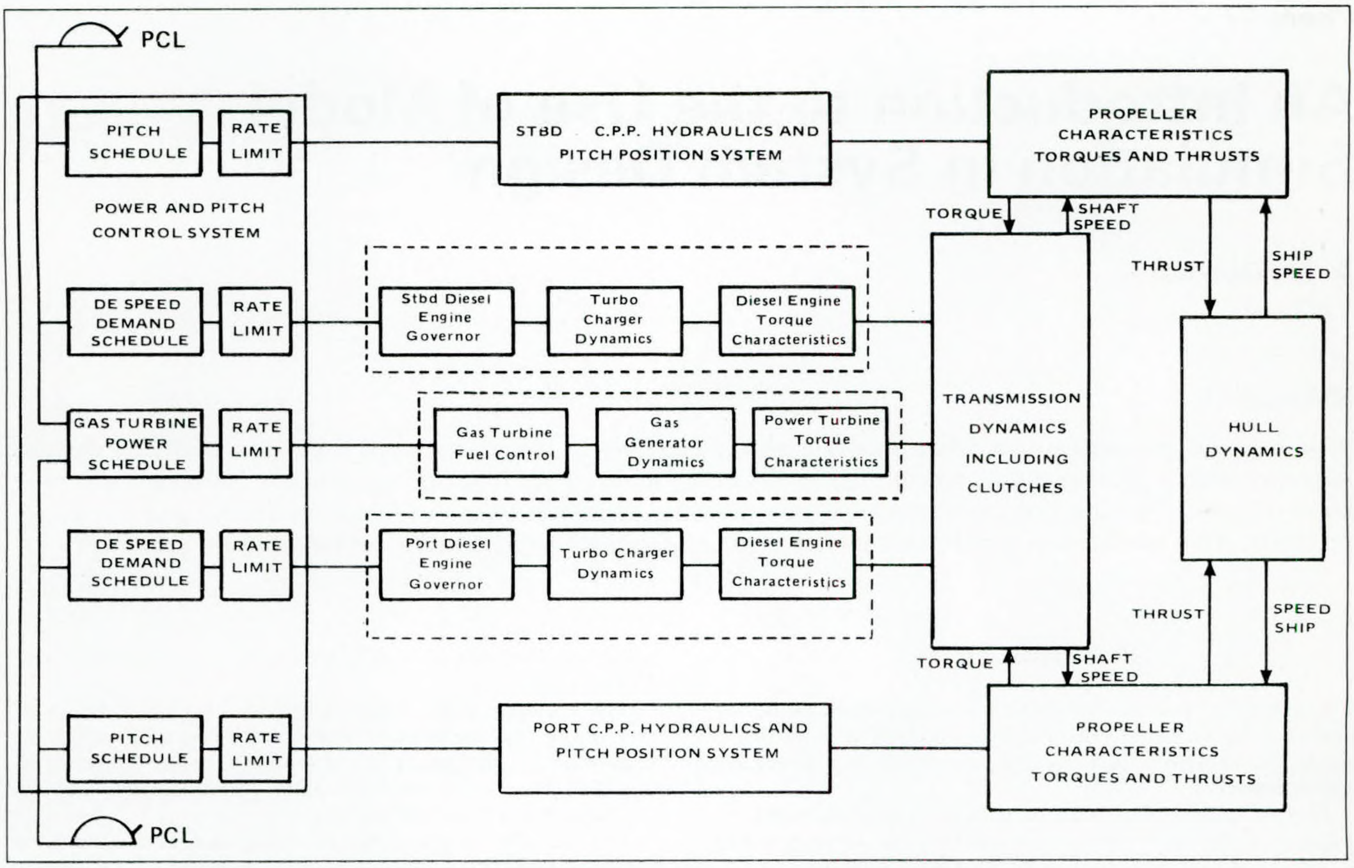


FIG. 1 Simulation model block diagram (CODOG propulsion system)

system non-linearities and time-dependent parameters but they are less suited to models requiring extensive 'look-up table' data which usually have to be implemented by, for example, diode function generators (DFGs). These DFGs are usually limited in number and time-consuming to set up.

Conventional mainframe or mini-computers, on the other hand, facilitate the use of many look-up tables within a model but, if accurate integration routines are used, then computation is relatively slow so that it can be difficult to achieve real-time operation for large models of complex systems.

For some time hybrid computers have been used in an attempt to get the advantages of both digital and analogue capability. In this case the analogue handles the differential equations and the high-speed logic while the digital does the number crunching and provides the look-up tables. The analogue and digital computers communicate through a purpose-built interface.

More recently array processors and special-purpose digital simulation computers with parallel processors have become available. These allow very large models to be implemented digitally while retaining the ability to operate in real time or faster.

With digital computers a further consideration is whether the model should be programmed with either general-purpose languages such as Fortran, Pascal, Coral, etc., or special-purpose continuous system simulation languages (CSSL) which are interactive and operate within the simulation environment (ie, can call existing integration routines, function generation/interpolation routines, etc.).

At YARD Ltd we have progressed through analogue, digital and hybrid systems and now use a special-purpose digital computer, the Applied Dynamics AD10 system with special-purpose software designed to take full advantage of the AD10 multiprocessor architecture. The AD 10 is hosted by a DEC VAX11/780 computer and the complete system is shown in Fig. 2.

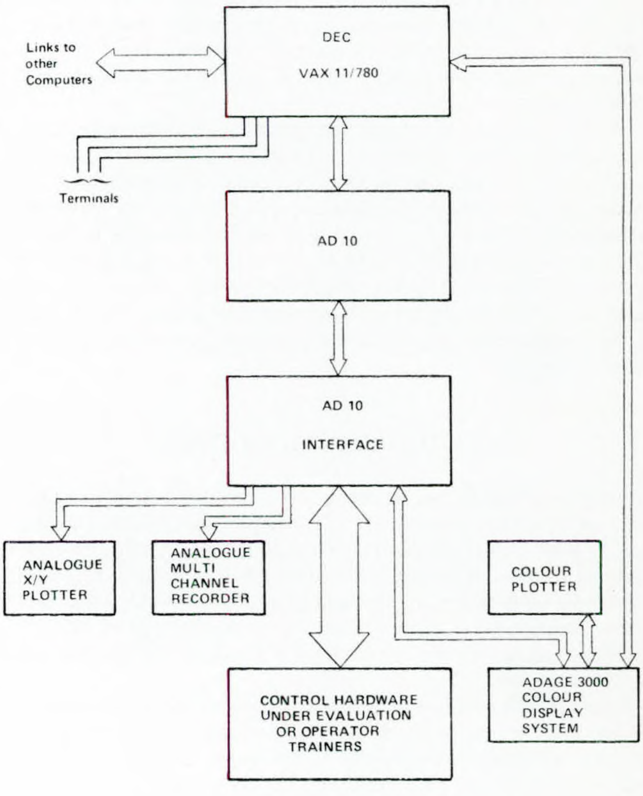


FIG. 2 Real-time simulation facility

Simulation process

It is essential that a rigorous process be used in order to get meaningful results from a simulation investigation. The model-building stage is manpower intensive (and is therefore the most likely area for human error). The model-run stage may use substantial computer resources which can be expensive. Unless the modelling is well controlled, either the computer runs will be useless because of mistakes in the model formulation, or project costs will rise because the model-run programme is not well thought out in advance.

Typically the major activities in a simulation investigation are:

Model formulation
1. define the problem and objectives and select type of model
2. generate mathematical relationships for the system
3. acquire data
4. document data basis
5. document model

Model implementation
1. select computer
2. program model equations
3. verify computer programs
4. validate model results related to real systems

Produce model-run programme
Run model
Analyse results.

Model validation

The mathematical model must have sufficient accuracy to give confidence as regards the particular answers expected of it. It is risky to produce an elegant simulation model of vast complexity if it cannot be validated or use validated data. Since prime movers are not usually unique to particular ships, it is often possible to use a model which has been validated previously, either by other ships' trials or engine test bed results. Propeller and hull data usually come from tank tests but these must be treated with caution and perhaps modified in the light of experience, because most tank tests provide quasi-steady-state data which in the simulation must be used to represent transient conditions.

In the offshore area other modelling problems arise. In many instances it is almost impossible to obtain full-scale trials data in advance because of the novelty of the system being analysed. One can only make the best judgement based on available data and existing knowledge of the system and identify those areas where the lack of hard data is critical to the design. In most cases it is possible to carry out sensitivity analyses and use good engineering judgement, based upon these, to influence the final design. In certain cases special tests, at full or model scale, of system parts may be necessary to help fill critical gaps in available knowledge.

An example of the comparison between sea trials and simulation results for a COGOG warship[1] is shown in Fig. 3. This is taken from one of the earliest gas-turbine warships before the model was adjusted to take account of trials experience.

The figure is on a base of time and shows traces of propeller thrust, propeller torque and ship speed. The figure shows that some model tuning would be necessary to predict peak propeller thrust accurately although one must also bear in mind that propeller thrust is itself difficult to measure precisely.

TYPICAL APPLICATIONS

There are many applications of simulation techniques in the marine field and a limited number of examples will be used to give an appreciation of what can be achieved.

Machinery control systems

Design

A ship propulsion control system should ensure good and consistent ship manoeuvring without overstressing the propulsion plant and be reasonably tolerant to system failure or operator error. The example chosen for illustration purposes is that of a typical small warship with a combination of gas-turbine and diesel engines for propulsion, a typical arrangement of which is shown in Fig. 4.

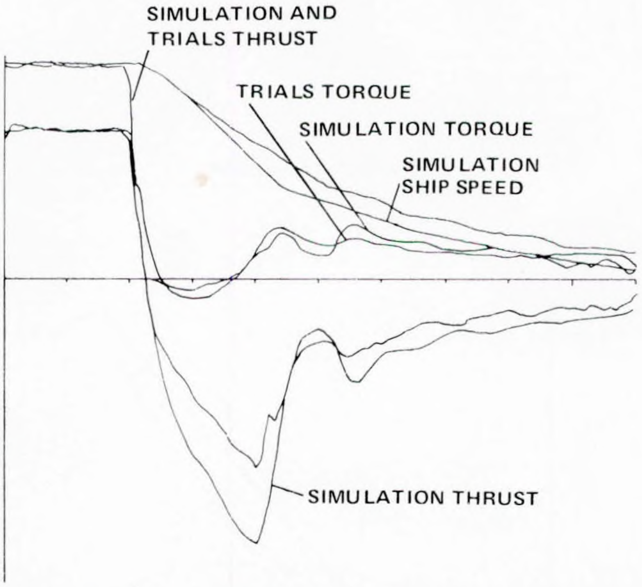


FIG. 3 Simulation model validation study including ship characteristics and a crash stop manoeuvre

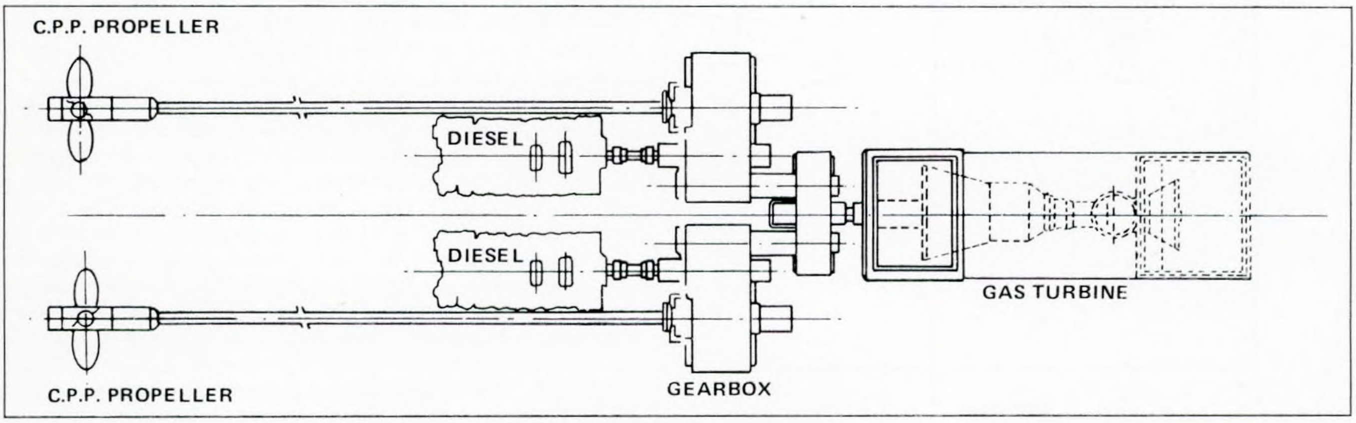


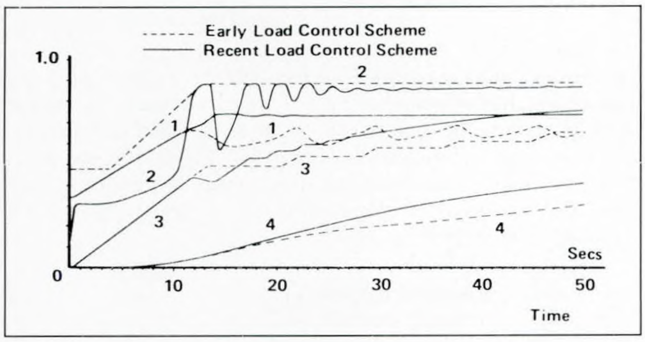
FIG. 4 Typical CODOG propulsion system

It comprises one gas-turbine and two diesel engines, driving controllable-pitch propellers through cross-connected reduction gearboxes. Propulsion is either by the gas turbine or by one or both diesel engines.

The program modules included in the mathematical model of the system are those shown in Fig. 1.

The control requirements in the diesel-engine drive mode illustrate the usefulness of simulation. The controllable-pitch propeller in a CODOG plant must obviously be sized to absorb the power of the gas turbine. With diesel-engine drive, small changes in propeller pitch result in high load changes on the lower-powered diesel engine, especially if it is the only diesel in use.

The high gain of the diesel governors causes large fuel-rack movements as the diesel speed reduces due to propeller-load changes. These engines are usually turbocharged and their rate of loading must be carefully controlled to prevent turbocharger surge. Therefore, a carefully designed control system is needed to adjust the application of load to the engine so as to avoid major excursion of fuel-rack position.



1 – Engine Speed
2 – Fuel Rack
3 – Propeller Pitch
4 – Ship speed

FIG. 5 Ship acceleration

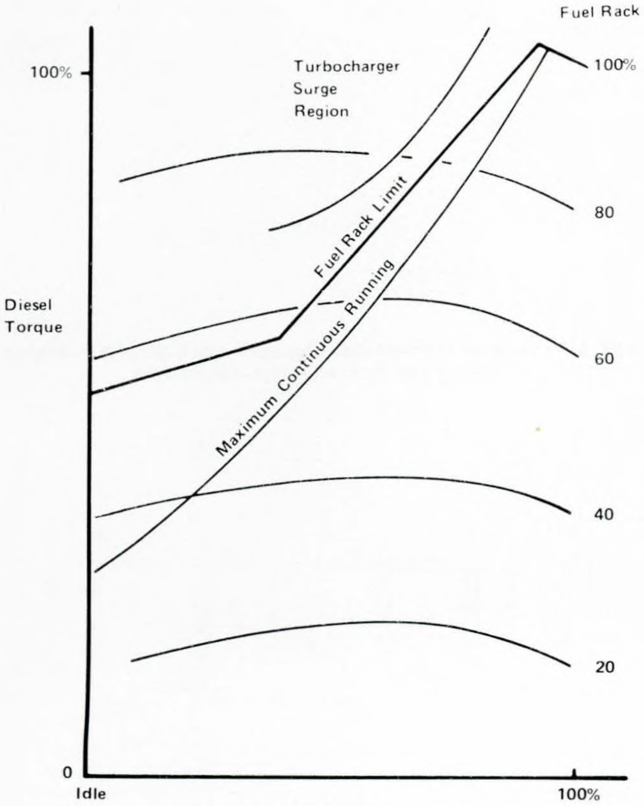


FIG. 6 Diesel engine performance map

Figure 5 shows a comparison of relevant parameters during a ship acceleration manoeuvre; the dotted lines relate to an early scheme which controlled propeller pitch as a function of engine speed error; the full lines show behaviour with a more recent scheme where propeller pitch is controlled as a function of both engine speed and fuel rack-position. The more effective load-control system, which is now in service, would have been difficult, if not impossible, to design adequately without the use of a computer simulation of the ship and propulsion machinery.

The requirement for diesel-engine load control is worthy of further explanation.[2] Consider the diesel-engine performance map shown in Fig. 6: it is common for a limit to be included within the governor to prevent the fuel rack supplying excess fuel and giving rise to turbo-charger surge. This fuel-rack limit in fact restricts maximum available torque at medium to high speed to only a little more than that required for maximum continuous operation. To obtain the best transient performance it is thus necessary for the load-control system to make use of the maximum available torque and prevent prolonged operation on the limit.

By using the simulation model as a basis for experimentation it has proved possible to derive control functions which will protect the diesel engine from surge and which will allow acceptable ship acceleration performance. Failure to use simulation methods for this control-system design would mean the risk of extended ship trials and possibly expensive system modification as a result of trials experience.

The diesel-engine model used in this example is relatively simple in concept but contains the major elements which influence the overall dynamic performance from part to full load. The model was derived from test-bed results and ship trials have shown it to give accurate prediction of system performance. Obviously a different form of diesel-engine model would be necessary if one were interested in, say, the thermodynamic performance of individual engine cylinders.

Acceptance testing

Once a control system has been built, it should be tested functionally, prior to installation on the ship. To provide the acceptable level of confidence that it will perform as designed, it is often exercised dynamically and a cost-effective method is to test it in conjunction with the original design simulation model of the plant and control system. An alternative would be to test it against shore-based plant but this sort of test facility is rarely available and testing would be very expensive.

Machinery performance assessment

Mathematical modelling can be used to assess the dynamic loading within the system during severe manoeuvring. This can allow major decisions to be taken at an early stage, such as the size of a friction clutch or the capacity of a cooling or hydraulic system.

Returning to the CODOG-powered ship discussed previously, it is interesting to look at the analysis of connecting a single diesel engine to a stationary mainshaft. In this case a diesel is initially running close to idle speed and the clutch is pressurised to start the shaft system rotating. The overall system performance depends on the control-system functions and factors such as static friction, low-speed torque limits and pressurising-rate control. These factors may not be accurately defined at the preliminary design stage or may have wide tolerances. Therefore it is important that a sensitivity analysis be carried out, using the simulation model, in order to specify acceptable control settings and equipment tolerances. This is particularly important where all the equipment items are procured independently.

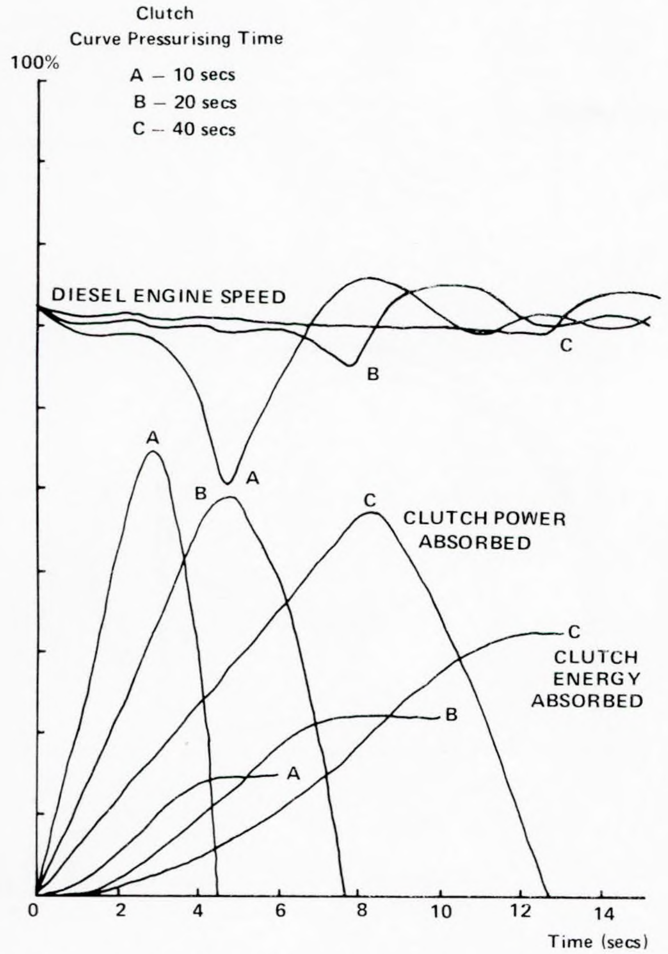


FIG. 7 Connecting diesel engine to a stationary shaft – effect of increasing clutch pressurising time

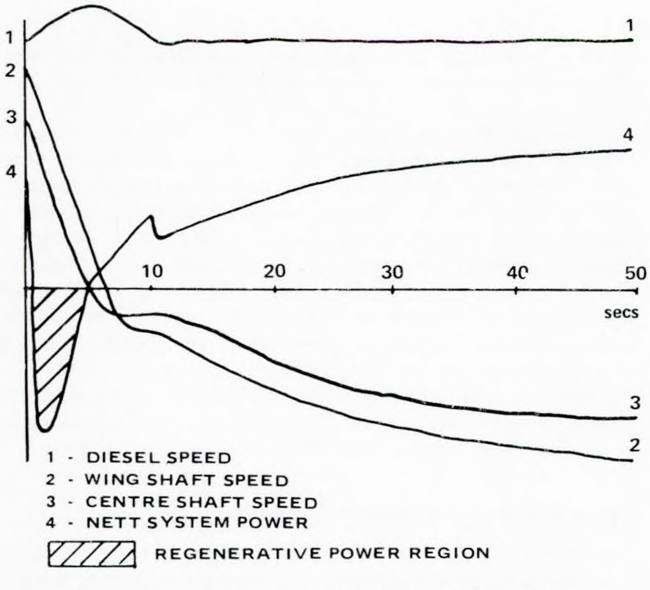


FIG. 8 Crash reversal – three shafts simultaneously

Figure 7 shows the effect on clutch power dissipation when the clutch is pressurised at different rates. Obviously the higher the pressurisation rate, the more severe is the load on the engine. In this particular case rate B leads to satisfactory connection.

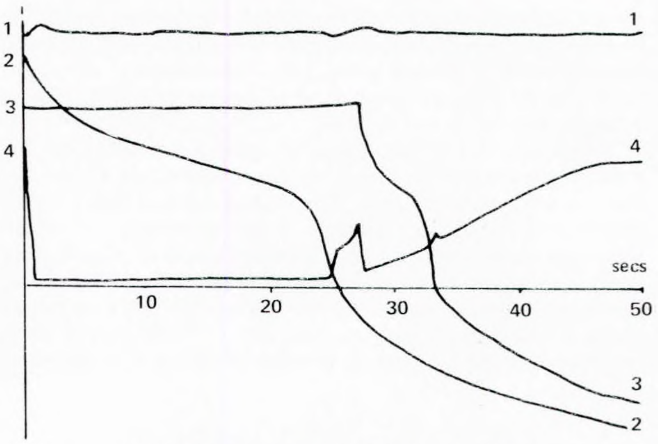


FIG. 9 Crash reversal – wing shafts first

Another example which illustrates the use of simulation in machinery studies is the work recently undertaken for a high-power icebreaking ship.[3] This is intended to have gas turbines driving electric-power generators. Ship services and propulsion systems are integrated, which means that the electrical consumers, including the propulsion system, are supplied from a common electrical source that imposes certain restrictions on the users. For instance, the need to maintain frequency within narrow limits poses problems during manoeuvring.

Normal procedure during high-power crash-reversal manoeuvres would result in the propeller pumping energy back into the system at a rate which could not be absorbed by the generating sets. A common practice in icebreaking ships is to use dynamic braking resistors to absorb this excess energy but these would have been expensive to use in this particular design.

A computer simulation of the total system provided the opportunity to judge the effect of different methods of operating the system. Figure 8 shows the results of a crash reversal without dynamic braking resistors and with the three shafts operated in unison. The shaded area on the power trace shows the energy being pumped back into the electrical system by the propeller.

This 'regenerative' power causes the diesel speed to increase since the electrical system is incapable of absorbing the energy. The diesel speed variation (and, hence, generator frequency) was unacceptable and an alternative method of control was to sequence the reversal of each of the three shafts. This was shown to reduce the regenerative power to a level which could be absorbed without excessive speed fluctuation, as shown in Fig. 9.

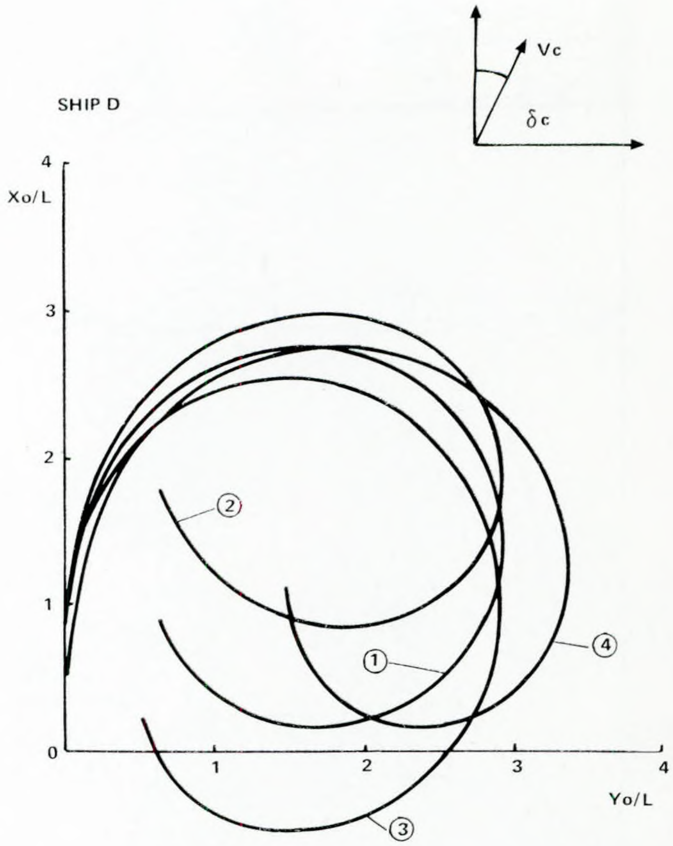
Thus a relatively inexpensive control modification saved the more conventional but expensive use of dynamic braking resistors. The decision would not have been possible without the evidence of the simulation analysis.

Manoeuvring performance assessment

Simulation can be used with good effect to assess the manoeuvring capability of ships in a wide variety of scenarios or design aims. Typical examples include crash-stop/slam-acceleration performance analysis; high-speed turning manoeuvres; collision avoidance system design; ship collision investigations; dynamic positioning system design; control of remotely operated vehicles; submarine depth control; and bridge training.

The majority of the above simulation examples require more explicit representation of environmental forces than is the case in propulsion control, and usually require consideration of the system performance over the life of the vessel, or at least across some sort of mission profile.

For example, the design of the dynamic positioning control system requires the environmental forces on the ship to be characterised in a statistical form and the simulation model has to be re-run with these parameters, or combinations of these, varying in some random form. This is an extension of 'worst-case' design and can often lead to significant reductions in system cost.



	Current Velocity Vc (knots)	Current Direction δc (day)
①	0	0
②	1	0
③	−1	0
④	+1	90

FIG. 10 The effect of uniform current on turning performance

Validation of simulation models against full-scale data for some of these manoeuvring models can be difficult. Figure 10, for example, shows a plan view of a simulated ship turning manoeuvre in varying uniform-current conditions. It can be seen that modest currents can have appreciable effects. This would have to be taken into account if the trial positions were being measured in absolute terms, using SATNAV or shore-based position-fixing systems. The effects would be less obvious in comparing the relative position of two ships in the same area.

Dynamic loading in offshore systems

An application which illustrates what such models are capable of is the launch and recovery of remotely operating vehicles (ROVs) from ships or semi-submersibles.[4]

The system in Fig. 11 shows a large ROV being deployed from a semi-submersible. The deployment can take place in reasonably high seas and considerable dynamic loading can arise between the vehicle and lifting apparatus. To analyse this it is necessary to construct a mathematical model which represents at least the motions of the mother vessel and of the ROV; wave elevation, velocity and acceleration; crane and winch controls; and hoist-rope non-linearities (especially slack rope).

The motions resulting from the irregular forces due to wave action have to be predicted in six degrees of freedom.

Figure 12 shows the simulated results, typical of such a vehicle when launched through the air/sea interface. This figure shows the vertical position of the vehicle, its depth of immersion and the tension in the lifting rope. It clearly indicates the large variation in forces and motions sustained during transit of the interface.

The elements in the above model can be re-arranged and additional modules added to allow examination of, for example, heave-compensation requirements of diving bells; replenishment at sea (RAS) rig dynamic loading (between two ships); mooring requirements of tankers connected to North Sea production buoys; and dynamic crane loading.

At the design stage, simulation data for the mathematical model will only be available from tank tests and one must be aware of the areas where these may differ in the full scale.

Closely related to the ROV recovery is the dynamic load imposed on the cranes of fixed offshore platforms when these are used to lift large loads from supply boats in high sea states.[5] A comparison of simulation and measured crane-boom loading is reproduced in Fig. 13. The agreement between trial results and simulation was very good although the hoist-rope damping had to be revised to improve representation of the higher-frequency components. Even before this update in damping the original model accurately predicted the peak forces in the system which occur early in the lifting operation.

Another area receiving considerable attention at present is the prediction of environmentally induced loading on flexible production risers which will be used increasingly in the development of marginal fields in the North Sea. Flexible risers, umbilicals and mooring lines form a class of system which can be represented by slender elastic cylinders. Any dynamic representation of such a system forms an arduous computational load which arises from the large number of elements necessary. The inherent non-linear nature of the problem prevents the easy use of time-domain solutions. These non-linearities can be classified as those:

1. arising from large displacements
2. associated with variable boundary conditions
3. associated with hydrodynamic loading (drag and vortex shedding).

The model developed by YARD uses a finite-difference solution to the full three-dimensional problem. The representation includes waves; sub-sea buoys; stretch; bending; and current profiles.

Under low-frequency wave excitation, cables/risers could be described by a few low-frequency transverse-vibration modes, plus a few longitudinal modes of significantly higher frequencies. If a discrete (ie, lumped mass) simulated approach is adopted, then, with digital integration methods, the stability of the longitudinal modes dictates the speed of solution. Adoption of a body-related axis system allows the longitudinal equations to be isolated and solved more frequently than the lower-frequency transverse equations. This multiple framing allows the model to run significantly faster, up to real time.

Although real-time running of the model is not an operational requirement, it does, in this case, allow substantially more runs to be carried out within a given computer budget.

Operational performance assessment

The use of simulation techniques for operator performance assessment requires real-time operation of the mathematical model. The common forms of this technique are training simulators, common in the aerospace industry, and most often used in the marine area for ship's bridge simulations.

It is possible to use real-time simulation at the design stage of control rooms for complex systems to ensure that complete and safe operation of the system is possible by the requisite number of operators without unacceptable workloads.[6]

As part of a military design programme for nuclear-plant

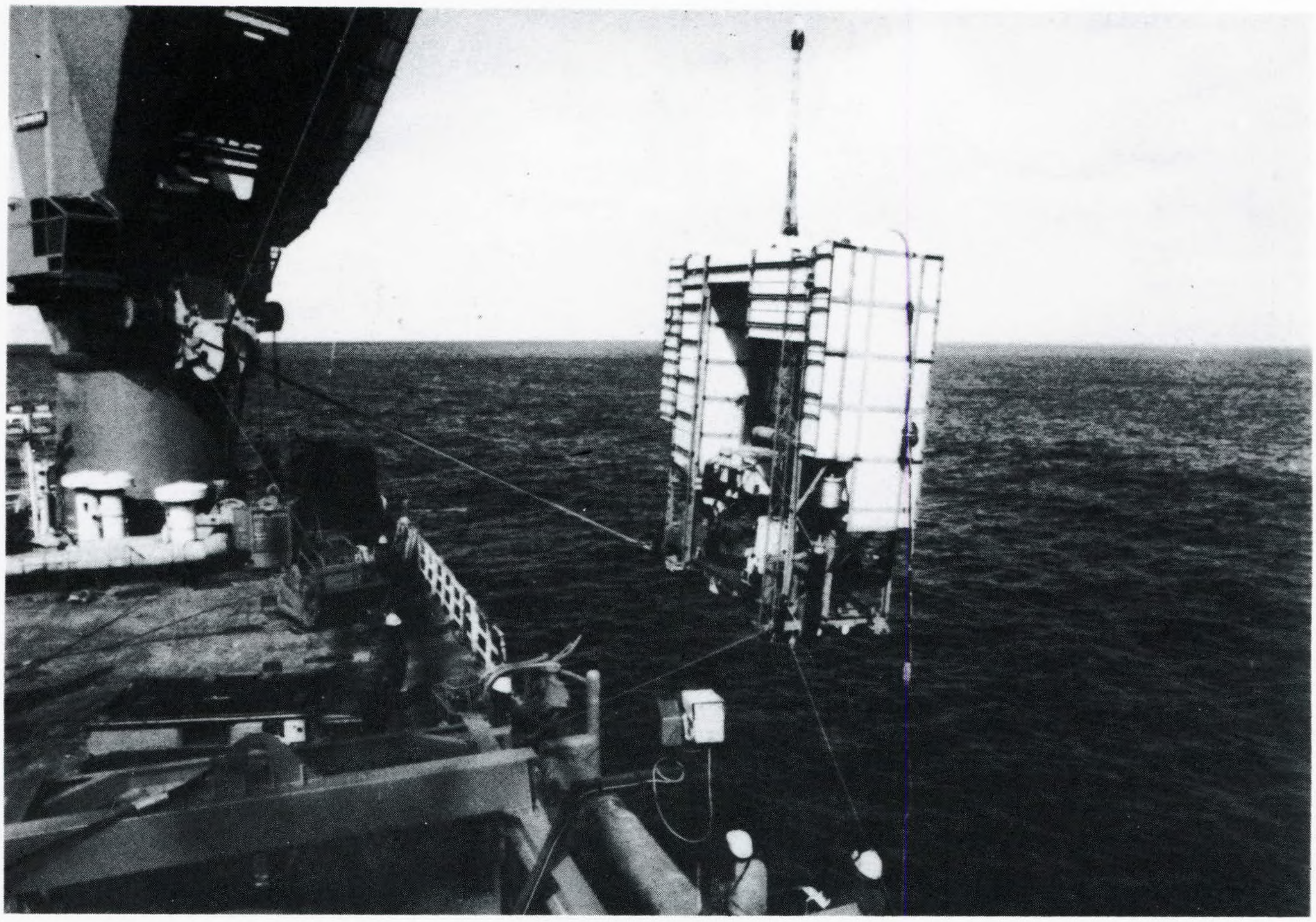


FIG. 11 ROV deployment

control panels it was important to draft operational procedures covering both normal and emergency situations. A plant-control-room mock-up was constructed to act as a focal point for this work. As the design progressed, the mock-up was connected to a real-time simulation system to provide an added degree of realism and to afford operators the opportunity to assess the design more easily.

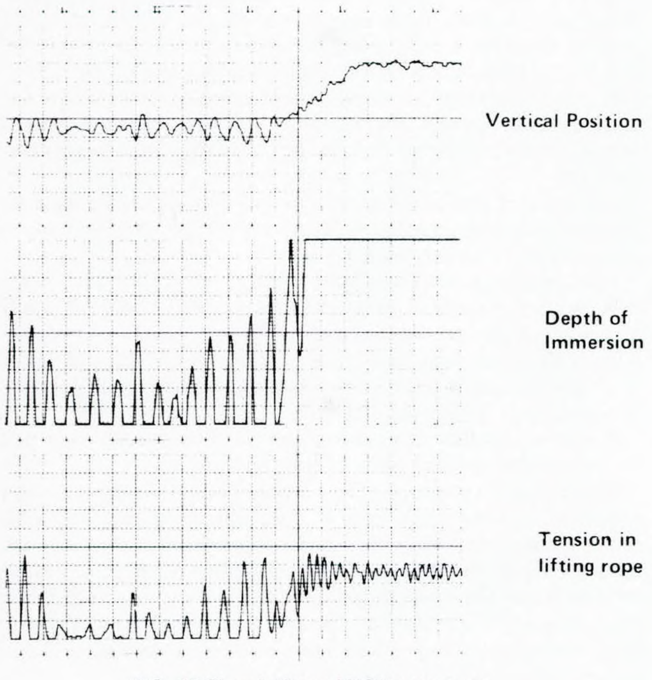


FIG. 12 Simulation of ROV recovery

The degree of confidence in the final design depends to a fair extent on the degree of realism provided by the simulation at early stages in the design or during the assessment periods. It is a natural evolution for these practices to carry over into operator training when the systems have entered into service.

It is not surprising that large simulators of this type are fairly expensive to design and produce. However, the overall training in some areas of the industry can be subdivided into more manageable tasks. For the more complex of these tasks a smaller training facility can be provided. These so called 'part-task trainers' can often use desk-top computers and be implemented very cost effectively; their use is growing fairly fast in, for example, the offshore oil and gas industry.

Another aspect of operational performance assessment is the testing or assessment of operating equipment. For instance, it has become common practice to test the functioning of complex control systems by simulation methods. The control system and, more importantly in some cases, the protection system can be exercised over its full operational range by connecting it to a simulation of the plant to be controlled. The advantage is that solving problems at this stage can save time when setting the actual plant to work and plant damage due to design or construction defects in the control system will be avoided.

FAILURE EFFECT ANALYSES

The use of simulation allows the effect of serious system failures to be quantified and permits compensating measures to be analysed, particularly when the failures are too expensive or hazardous (as in the nuclear industry) to analyse using the actual system.

Analysing the effects of system failure by simulation techniques has an obvious drawback: except in very special

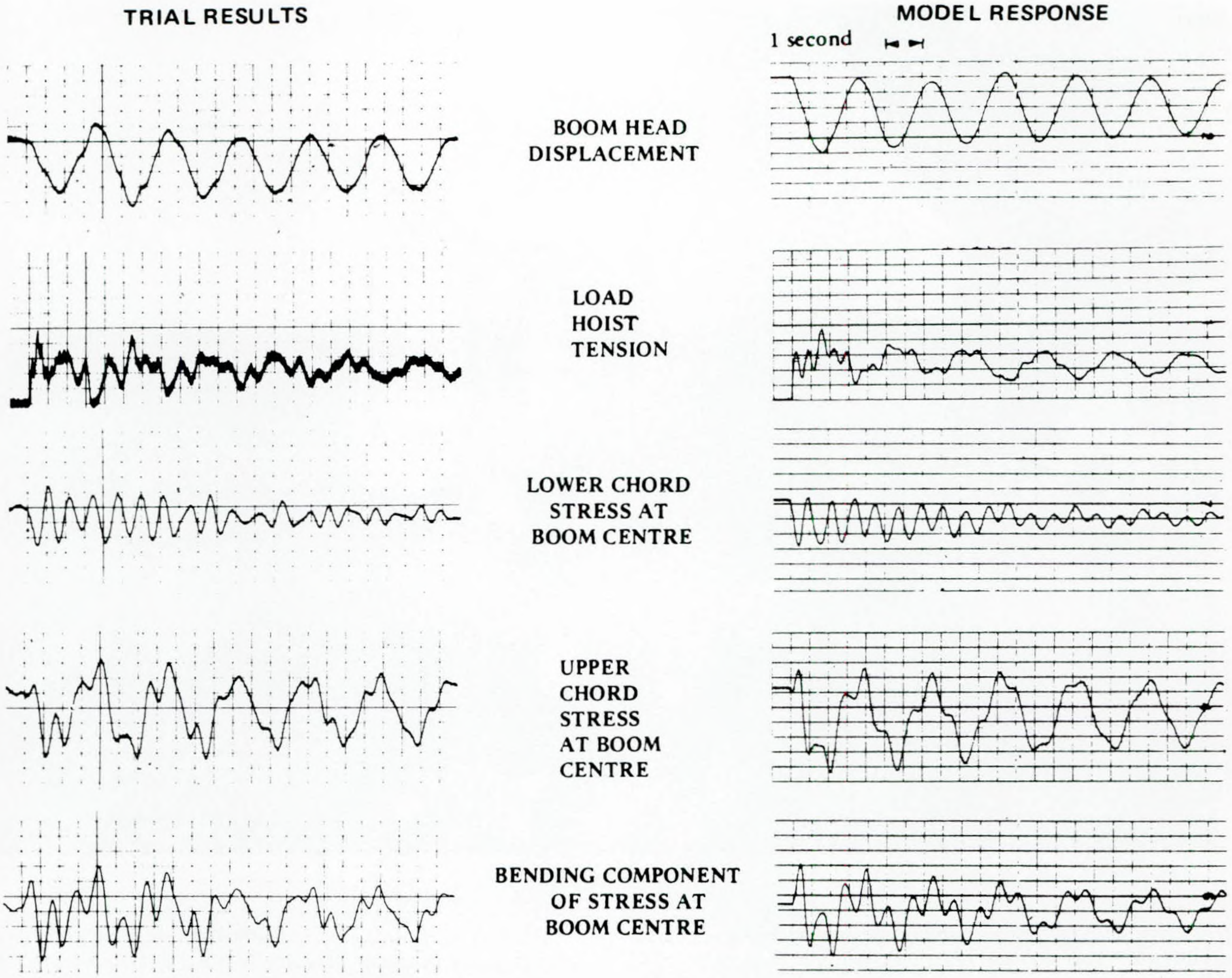


FIG. 13 Trials results compared with analog model response revised damping

circumstances, it is unlikely that validated system data will be available. One must take great care, therefore, in extending a simulation model to examine failures. However, in very many cases existing system knowledge, together with classical engineering analysis, allows a model validated for normal operation to be extended for failure analysis.

Such extrapolation is almost always acceptable and accurate when examining protection-system design because the state of system knowledge will usually be reasonable up to the protection limits; but when extrapolating the model of a highly non-linear system well beyond normal operating limits care is necessary. In some cases a sensitivity analysis of the effect of system failures to changes in the data thought to be most difficult to validate helps to put bounds on the likely severity of the failure.

DISCRETE-EVENT SIMULATION

Discrete-event simulations are characterised by the occurrence of events at random times and are, perhaps, best exemplified by considering the queuing situation of people arriving at a Post Office. The best known applications of this technique within marine engineering are in the fields of reliability and availability; and operations (eg, transportation analysis).

Reliability and availability

Much of the work in the field is done by analytic techniques such as Markov analysis but sometimes when there are many alternative configurations of equipment that can satisfy requirements it is necessary to revert to simulation techniques. When this is done each component in the system must be characterised by a mean time to failure, mean time to repair and likely distribution of these times about the mean. Obviously the situation is complicated when it is possible for equipment to operate intermittently and it is sometimes necessary to provide separate figures for the likelihood of a successful start.

A typical situation involved a propulsion system containing four diesel engines, four generators and two propulsion motors plus associated switch gear.

The simulation consisted of:

- A static data base, containing failure and repair rates and various power and speed parameters;
- A dynamic data base showing the state of the system at any instant of time; in this case the state of each component and the required speed;
- An event file, containing the various speeds that are scheduled to take place in the simulation.

These models produce a large amount of data and it is always necessary to have some form of data collection and reduction at the output end. They also suffer from the fact that it is not always easy to disentangle cause and effect within the model structure but these methods have been used successfully in many studies of machinery systems and vessel effectiveness. Such models usually give confidence factors rather than clear-cut absolute results.

Operations

The methods used are derived from the field of operational research which is widely applied in civil engineering and other land-based industries. The models tend to be characterised by the time of arrival and the time taken to service the vessel. A typical example was the disposal of sewage at sea via a fleet of vessels which had to use a lock system between the loading point and the ocean. The questions to be answered concern: sizes and speeds of the vessels; filling/emptying time of the locks; the cost of providing the above; and the on-shore storage capacities required.

A further example is the supply and service of North Sea installations where the trade-off is between the on-board capacity of the installation and the likelihood of a particular vessel design being able to operate under the weather pattern prevalent in the area.

ELECTRICAL-POWER-SYSTEM ANALYSIS

Early in the paper mention was made of the use of general-purpose simulation packages. The YIPSA (YARD Interactive Power System Analysis) program has been developed in collaboration with UMIST, specifically for the design of electrical systems in marine applications.

The original UMIST program is used extensively throughout the supply industry and both programs are packaged in an integrated format to produce load flows, short-circuit analysis and detailed dynamic studies for specified system configurations. The dynamic analysis allows the study of such dynamic phenomena as the transients during motor starting, load shedding or fault recovery to ensure the overall stability of a system.

FINAL COMMENT

Simulation provides marine engineers with a powerful tool for use in system design which, if properly applied, will reduce the risks and costs of major projects. The technique is not necessarily expensive and, for many applications, modest investment can yield significant improvements in design and operation of systems.

For many years the technique has been at the heart of operator training simulators in many industries and there is every indication that there will be a growing trend in this area as computer hardware costs continue to fall.

It is emphasised that care is needed to ensure the mathematical model is fit for the purpose intended, both in its construction and as regards the data used. Whenever possible account should be taken of any actual test data available.

Lastly, experienced engineers must be heavily involved in any simulation analysis, both to ensure that the model will do the job, as indicated above, and, most importantly, to provide the judgement so necessary when interpreting the results.

ACKNOWLEDGEMENTS

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