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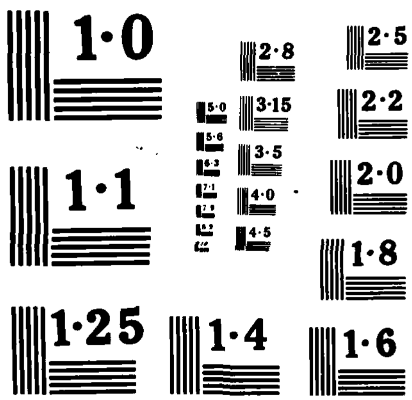
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VOLUME 5

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SESSION R:

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A NEW LOOK AT SOME OLD SHIP HANDLING PROBLEMS EMPLOYING CAORF'S MAN-IN-THE-LOOP SHIP SIMULATOR

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ABSTRACT

The paper treats the general characteristics of the man-in-the loop ship control problem and the effects of instrumentation and other aids to navigation on safety, precision and efficiency of shiphandling under the harbor approach and restricted waterway conditions. The availability, accessibility and processing of navigational aid information and their effects on man-ship interactive behavior, is presented and discussed in terms of the research approach utilized in the National Maritime Research Center's human factors research using the Computer Aided Operations Research Facility (CAORF). The parameters of concern include types of information displayed, cognitive work load, shipboard navigational aids (instrumentation) and enviromental navigational aid (buoys and other fixed references).

The types of shipboard navigational aids considered ranges from raw visual data unsupported by electronic instrumentation to the latest computerized systems now in use and under development. Fixed references considered include varying buoy configurations and their effects on the man-ship reaction relative to ship controllability.

INTRODUCTION

This paper presents a descriptive summary of some of the research conducted at the National Maritime Research Center utilizing the full scale ship simulator, the Computer Aided Operations Research Facility (CAORF) at Kings Point, New York. This facility was established to investigate the man-ship-environment interaction. The research to be reported is structured in such a way as to emphasize the importance of determining what information the man must have available and accessible in order to ensure safe consistent and reliable ship control.

Technology has over the recent past developed highly reliable instrumentation with relatively little error and more accurate systems are under development today. The problems of ship control, however, are in some ways independent of the accuracy of the state-of-the-art technology. One problem is quite simply a variation in reliability or predictability of man's response as a consequence of information assimilated by him. Engineering precision is of limited value if the instrumentation or navigational aids produce a wide variation in response on the part of a ship operator. Reducing the response variance of the ship handler and consequently the ship is the key issue. Therefore, in order to improve ship handling one must first determine the variance of the human under specific problem situations relevant to the maritime environment. Consequently, one hears many arguments addressing the concept of human error. Ultimately, one wishes to determine the sources which initiate human error (the product of human variance) in ship handling and thus come closer to controlling and limiting variability in the man-ship reaction.

The issues which are given a high priority by the shipping industry are Productivity, Safety, and Economy. The first two are of major concern at CAORF both in the open sea traffic situation (harbor approach) and in restricted waterways. As in the case with most maritime problems, little is known about human variability and its impact upon productivity and safety. Although the human factor has obvious impact, its sources are little known. At CAORF, the National Maritime Research Center is regularly conducting experiments to compare the traditional navigational aids (both shipboard and fixed environmental references) with the more recent state-of-the-art navigational aids for both the open sea and in-harbor environments. The most important targets for research with respect to these problem areas are information input -- information processing -- decision making -- and ship response. Some of the questions which have been raised concerning these research objectives are:

A. What information does the shiphandler need in order to insure a safe, productive voyage?
B. How best can this information be made available so as to reduce human error?
C. What design criteria need to be established to ensure required safety with economy?

TRAFFIC CONFLUENCE IN THE OPEN SEA

The first experiments[1,2,3] conducted at CAORF were concerned with various shipboard navigational aids and the effect of such aids on the safety and productivity of vessel transit under varying traffic and varying visibility conditions. The shipboard navigational aids examined were:

A. The watch officer's raw visual data with Pelorus unsupported by electronic aids
B. Traditional radar
C. A Marine Radar Interrogator Transponder (MRIT)
D. A Computerized Collision *Avoidance System* (CAS)

The results of these experiments indicated that watch officers using the computerized collision avoidance system in traffic situations maintained greater distance from the threat vessels (i.e., closest point of approach, CPA) maneuvered earlier in time resulting in larger Time to CPA (TCPA), and traveling farther along their ideal track than did watch officers using radar or their own visual apparatus with Pelorus. Additional data indicated that this was the case in limited as well as unlimited visibility[4]. However, in the case of limited visibility, performance using radar was degraded as compared to the performance using radar in unlimited visibility. On the other hand, performance using a collision avoidance system (CAS) improved under conditions of limited visibility (see Figure 1). Moreover, when looking at performance under low to high traffic density conditions, it was again found that radar performance was degraded going from low to high traffic conditions while CAS performance was improved (see Figure 2).

In accordance with CAORF research philosophy, the staff proceeded to determine the sources of information which were responsible for such reliable findings[5]. As may or may not be known, the computerized collision avoidance system supplies both graphic image information on the Planned Position Indicator (PPI) as well as digital alphanumeric information displayed on a data terminal. The question to be answered was "What type of information (i.e., graphic or alphanumeric) was producing this desirable effect?" Additional subjects were tested using

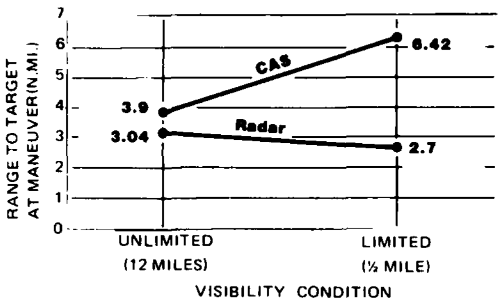

Figure 1. Interaction of Navigational Aid & Visibility

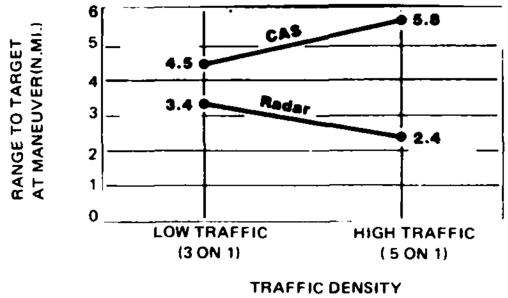

Figure 2. Interaction of Navigation Aid & Traffic Density

CAS without the data terminal alphanumeric presentation of CPA, TCPA, relative velocity, speed of other targets, etc. These subjects were allowed to use the CAS with only its graphic image display. The results obtained were the same as before. Using CAS without the data terminal produced results which were equivalent to those obtained when the test subjects had both the graphic and alphanumeric information simultaneously. It, therefore, appears that the graphic display supplies the watch officer with the information necessary to produce cognitive actions resulting in improved ship handling behavior. Other analyses concerning the consistency of maneuvers made using radar, CAS, or simply the visual apparatus plus a Pelorus indicated that uncertainty was reduced while using the CAS as compared to the radar condition and the visual only condition[6]. In traffic, the maneuvering behavior of ships equipped with a collision avoidance system was most predictable with less variation.

A further study, conducted at CAORF, was designed to determine the effect of intention to maneuver on the part of a threat vessel equipped with a Marine Radar Interrogator Transponder (MRIT). Using a MRIT, the watch officer of Own Ship (i.e., the CAORF vessel) could request the intention of a potential threat vessel and receive a coded digital response, each code being associated with a different meaningful intention on the part of the threat vessel (e.g., intend to turn to port, starboard, stand on, etc.). Being informed of the action taken on the part of a threat vessel should reduce the threat of collision and increase the consistency of ship maneuvers. Knowing the intent of the target vessel, however, did not increase CPA over that which was recorded by ships equipped with a graphic PAD (Predicted Area of Danger) display. Figure 3 demonstrates that although ships equipped with MRIT received such significant information as the intention of a target ship, performance showed as much variation as that of the radar and visual only case. Watch officers on

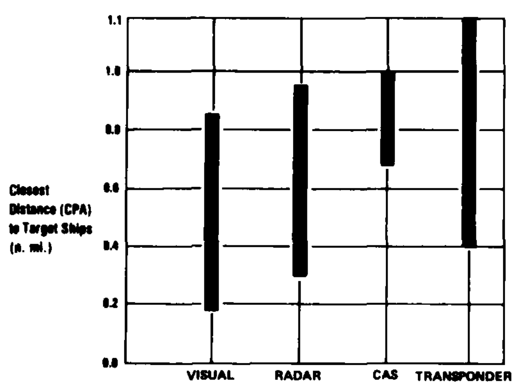

Figure 3. Range of Variation of Mean Closest Distance (CPA) to Target Ship

bridges equipped with a CAS on the other hand maintained large CPA's but did so with *little* variation and consequently, in a more predictable fashion (see Figure 4).

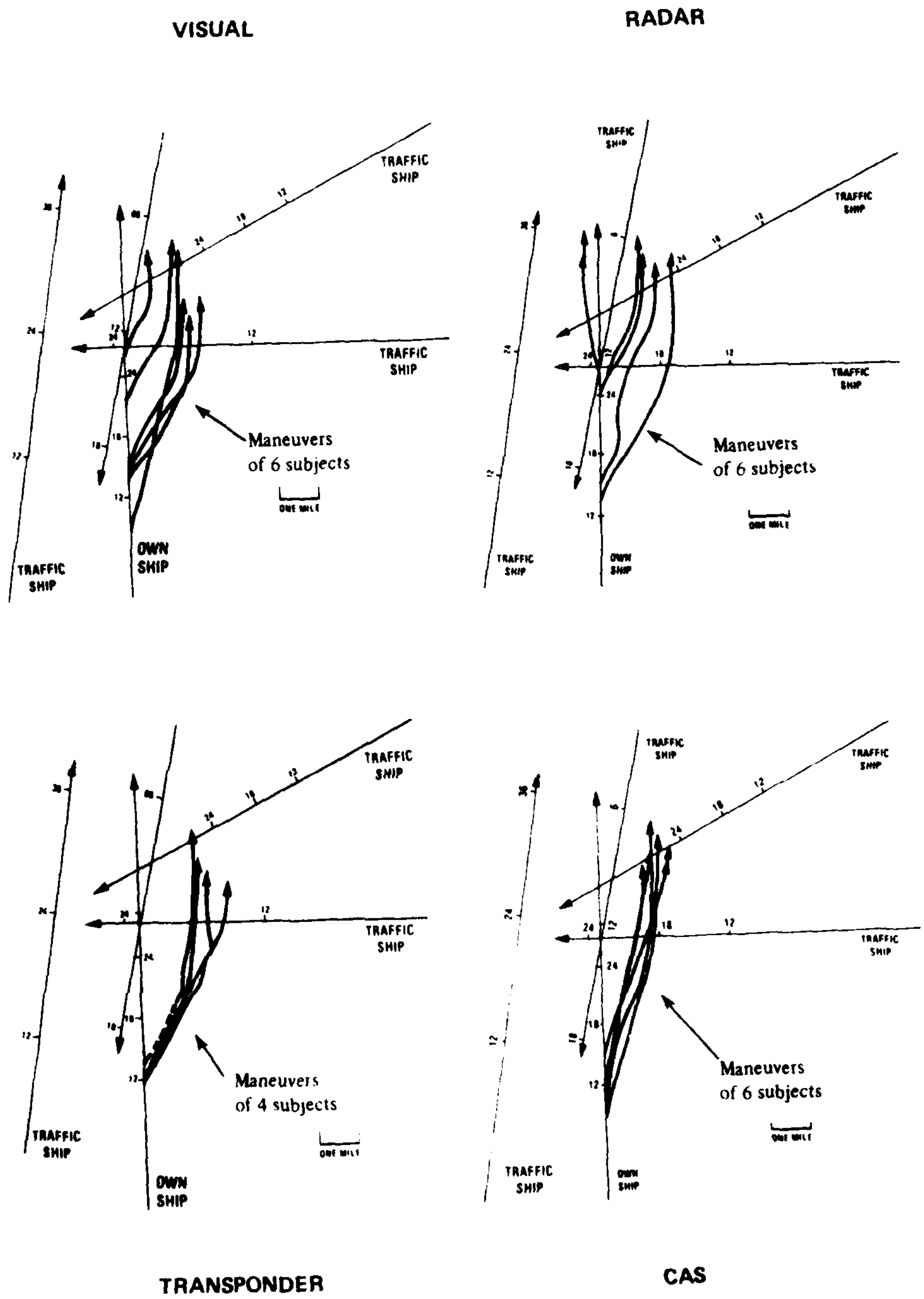

Figure 4. Ground Tracks for All Test Subjects

It therefore appears that with the instrumentation investigated in the open sea traffic situation, the man-ship interaction is less variable (i.e., more predictable) and most consistent using a computerized collision avoidance system, specifically with a graphic PAD display. It is this consistency in man-ship performance one must induce in order to increase safety. With such consistency in ship response one can then make more reliable decisions in maintaining a safe voyage.

Moreover, it appears that advanced communication of the intent on the part of a potential threat vessel does not increase the reliability or decrease the variation in the man-ship reaction as is demonstrated by the wide variation of ship response in the transponder condition (see Figure 3) compared to that of the CAS condition. The result of these experiments which indicate that the ship handler exercises more consistent and reliable behavior when supplied with graphic pictorial information as opposed to alphaneumeric or digitally coded data would support the notion that the digital data is of low information content in terms of its effect on decision making. More concisely, the amount of data available is increased by the MRIT system and the digital data terminal but the amount of information processed does not increase proportionately with the magnitude of data. In this case then one must carefully distinguish between the amount of information and the amount of data[7].

RESTRICTED WATERWAYS

More recently, experiments conducted at CAORF have been concerned with ship controllability, given differing fixed environmental navigation aids and varied shipboard navigation aids in restricted waters. The first of these experiments might be referred to as a new look at an old problem, that is, the effects of buoy spacing (i.e., 3/8 mile and 3/4 mile) buoy configuration. (i.e., parallel and staggered) and bouyed channel width (i.e., 800' and 1600') on track keeping. The variability in ship controllability, measured as a deviation from a prescribed track line, was analyzed for both channel approach and within the channel proper, under unlimited visibility. The result of this initial work indicated that track keeping variability was not dependent upon the use of shipboard radar when compared to the man without any shipboard electronic aids (visual cues only). That is pilots performed equally well using the raw visual data in the absence of any electronic aids -- for both channel approach and within the buoyed channel proper. More interesting results, however, were found in the analysis of buoy spacing, channel width and buoy configuration. For the approach path, the analysis of variance revealed that there was significantly less deviation from the track with the staggered configuration than with the parallel configuration. Additionaly, with the approach path to a narrow channel (800') there is more rudder action and greater deviation about the track line than there was found for the 1600' channel approach.

In the channel proper, track keeping showed less variation under the staggared configuration than the parrallel configuration and less deviation from the reference track with the 3/8 mile buoy spacing than with the 3/4 mile buoy spacing. Regarding channel width, track keeping exhibited greater variability for the narrower (i.e., 800') channel width than the 1600' channel width. It would thus appear that the use of information concerning the frequency and configuration of buoys in a channel can account for varying degrees of ship control. Channel width also obviously effects the ship handlers consistency in maintaining the position of the vessel within a specified reference track. The narrower the channel the less consistency in track keeping. Evidently, the pilot feels more confined in narrow channels and consequently overcompensates for any perceived deviation from his track line with a higher frequency of buoys. With the increase in buoy frequency more judgements with respect to perceived deviation from the track are made which leads to a high rate of rudder commands to re-establish desired ship position. With an increase in stress related information, as is the case with 3/8 mile spacing in an 800' channel, the rate of information processing with respect to position checking increases resulting in a greater number of rudder commands and an overcompensation of perceived errors in position determination, resulting in more erratic track keeping.

Figure 5 demonstrates the effect of information stress in terms of ship controllability as measured by deviation from reference track. This figure depicts the interaction of channel width and buoy spacing. As can readily be seen from this figure, track keeping depends not only upon channel width but also buoy spacing. The most erratic situation in terms of ship controllability occurs for the 800' channel width along with 3/8 mile (i.e., high frequency) buoy spacing. Information stress is created by knowledge of the channel width coupled with the high rate of information concerning ship position due to the frequency of buoys. This condition will lead to less consistency in ship controllability on the part of the pilot. However, if the magnitude of information is reduced in a stress situation it can be assimilated and acted upon resulting in greater controllability with less variation. This is the case which arises with an 800' channel width and a 3/4 mile buoy spacing situation. At the other extreme, one would assume that in the absence of information, consistency in track keeping would be degraded. However, at some point between extremes an adequate level of arousal, unencumbered by the stress of confined space, along with a relatively high frequency of buoy information, track keeping performance can be optimized. It appears from the data that the wide channel condition (1600') with a 3/8 mile buoy spacing approaches the state of optimal information flow created by frequently occurring information (buoys) in a moderate stress condition. As can be seen from an inspection of Figure 5, track keeping is most consistent for the wide channel with a high frequency of buoy information and for the narrow channel with a lower frequency of buoy information. One can extrapolate from the functions plotted that with wider channels and lower frequency of buoy spacing, consistency of track keeping will become progressively degraded. Likewise, in the narrow 800' channel with increased buoy frequency, consistency of track keeping will also become asymptotically degraded.

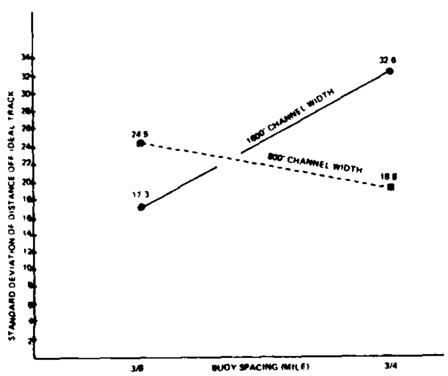

Figure 5. Interaction of Buoy Frequency (Spacing) and Channel Width

Although it has always been held obvious that the presence of buoys determined behavior to a certain extent, it was not until the completion of these fixed environmental navigational aids studies that these more interesting effects of buoy spacing and buoy configuration were discovered. As a consequence of these findings further research has been conducted to investigate the effects of differing navigational aids as they effect ship control in a turning maneuver.

Navigational Aid Configuration and Utilization

The next study to be described involved ship control in a narrow 500' channel with three turn points: a left 30° turn from the first leg (1 1/2 n.miles in length) to the second leg (2 n.miles in length). A right 45° turn from the second leg to the third leg; and a left 45° turn from the third leg (1 1/2 n.miles) to the fourth leg (see Figure 6). The dependent variables in this experiment were track keeping, that is, how well the pilots could maintain position and the number of excursions out of the channel. Four navigational aid conditions were experimentally investigated in unlimited visibility with radar information available continuously. The four navigational aid conditions were:

- A shipboard Precise Navigation instrument with only a lighthouse and land masses for radar position determination (Figure 7).
- Single buoys marking the inside of each turn point (Figure 8).
- Two gate buoys, one on the inside and one on the outside of each turn point (Figure 9).
- Range markers only, which could be used at each turn point (Figure 10).

In general, the results indicated that successful transit of the channel was not possible. Excursions of the channel were the rule not the exception. It was found that of the fixed environmental aids investigated, gate buoys improved performance in the approach to the turn and in pull-out from the turn due to the increased information of marking the breadth of turn area. The turn point buoy condition supplied insufficient information for the pilots to safely navigate the channel. This condition produced forereaching on all turns and bellying following pull-out from each turn point. The range marker condition also proved insufficient for safe navigation. Pilots using the ranges could not determine turn points but could successfully stay on line in the channel leg.

The condition employing the precise navigator instrument proved to produce the most successful transits of this extremely difficult channel. However, the pilots were apprehensive as to its accuracy and reliability. A major finding, here, was that although the precise navigation instrument produced the best results, it does not give point of execution of turn information. This crucial information, however, could be supplied by additional navigational aids (buoys) for a given channel and ship speed. Also of importance to note is that the pilots could learn to master the channel with very little learning using the Precise Navigator requiring on the average of three runs to become proficient.

The most recently completed experiment in this series of fixed navigational aids investigations was designed to give the pilot more buoy information for executing the turns and determining position in this same 500' wide channel. The navigational aiding conditions considered were:

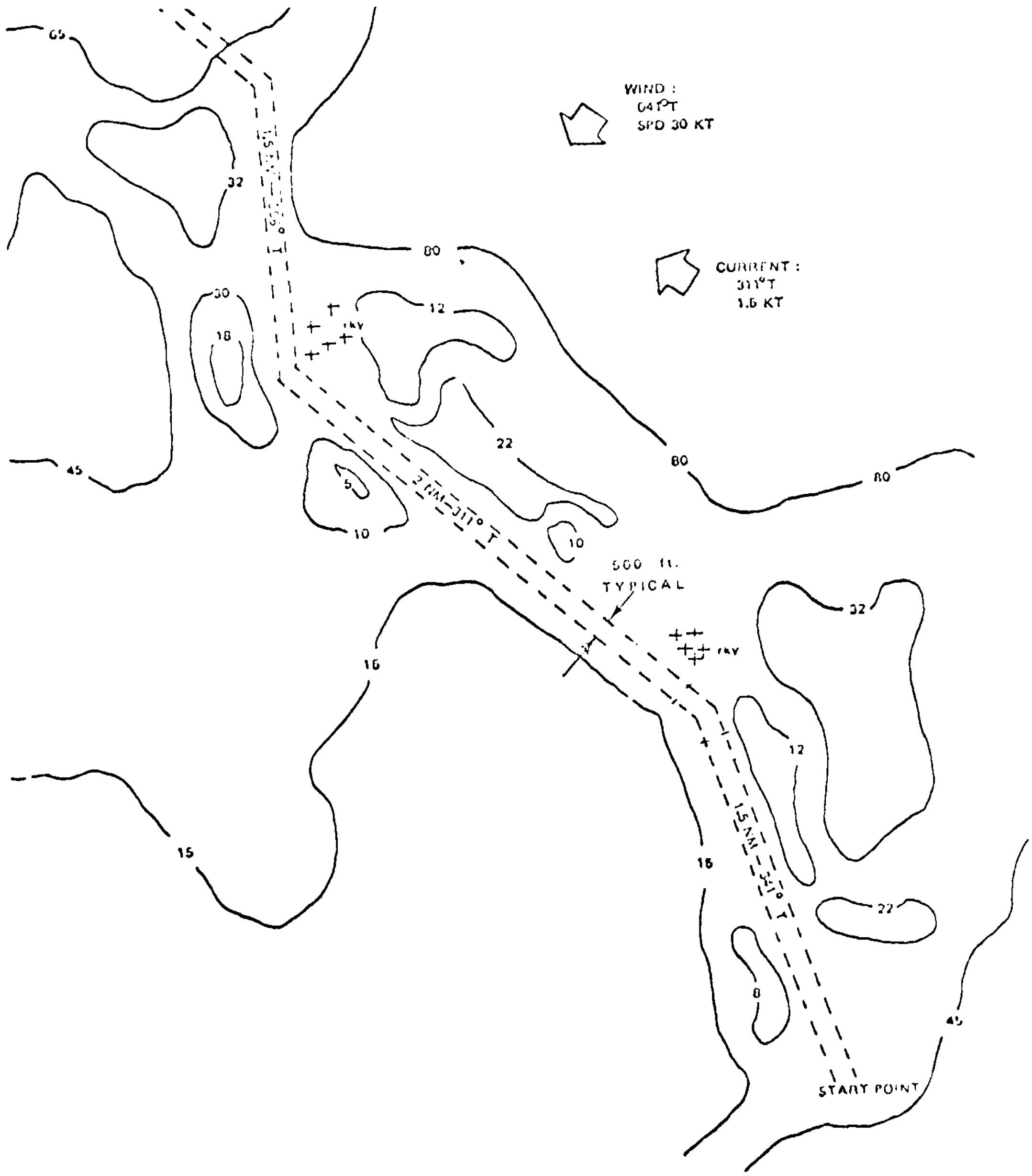

Figure 6. Channel Design for Restricted Waterways Experiment

Furthermore, preadaptation illumination levels in all previous studies for both red and white light were relatively high i.e. above 30 Lux. Actual shipboard usage of red light has been low i.e. 1 to 3 Lux. How would normal white light at low illumination levels in preadaptation compare with red light and with filtered white light in terms of the shortest time to darkadapt to the minimum practical illumination levels found at sea at night?

Considering the fact that fast adaptation processes due to neural mechanisms can span a range of 3 to 4 orders of magnitude, about all that is required on ship bridges at night, will this be sufficiently fast regardless of the wavelength which mainly affects the chemical process of the low level preadaptation light used?

NIGHT MYOPIA

To answer the above questions, an experiment was planned. During the planning another aspect of visual performance at night had to be considered which affected the experimental design. This is the poor accommodation capability of the eye at low illumination levels sometimes called "night myopia". Below 10^{-1} Lux the eye is not able to accommodate two objects at different distances. It always focuses to a fixed distance which varies with the subject and his age. In most published darkadaptation studies no mention is made of this effect, so it can be assumed that the subjects have not been tested for their night myopia. Leibowitz et al. (8) have published results of such accommodation experiments. They found that about 80% of the subjects tested focus in total darkness to a distance between 30 and 130 cm (12 and 50 inches). Based on these results it was necessary to test the focus of accommodation for each subject at low illumination levels (1 Lux) before using them in darkadaptation experiments to assure that they could focus our test objects. The focusing distance of our test objects was fixed at 80 cm. All our test subjects were able to focus within a range of 75 to 90 cm.

EXPERIMENTAL APPROACH AND SET-UP

The true approach to answering our questions was to preadapt each of the color normal subjects for at least four series to one of the test lighting conditions (i.e. 1, 3, or 10 Lux of white, filtered white, or red light) and then to test the time necessary for them to identify ship target aspect under various night viewing conditions. (9)

Preadaptation Light Sources

The light color and illumination levels need in the experiment were white, red, and filtered white at 1 Lux and red and white at 3 and 10 Lux. All light sources were produced by four 40 W incandescent light bulbs with neutral and/or edge filters. Red light was obtained by using a 610 nm edgefilter in front of the bulbs which stops all light below 610 nm (all except red). This filter reduces the original luminance of the incandescent bulbs to about 1/70th of unfiltered light. For the white light a neutral grey filter was used to reduce the luminance of each lamp to a level comparable to that of red light.

The filtered white light is obtained by combining a neutral filter to reduce luminance as mentioned above with a 485 nm edge filter. The edge filter stops all light below 485 nm (blue part) which constitutes only 3 to 4% of the unfiltered light of a bulb. Fig 5 shows the spectral distribution of white light (normalized, photometric estimated). The hatched area represents the blue part which is filtered out. The 3 to 4% intensity reduction of this edge filter was compensated by a slight increase of voltage so that this light source was at the same level as the others met.

By use of neutral filters for the white and filtered white lights voltage applied to the lamps as well as the illumination levels produced can remain about the same for the three light colors.

EFFECT OF COLOR ON VISUAL PROCESSES

A survey of the research literature concerning the physiology of the eye and the response of the eye to colored light was performed. One significant aspect of the human color visual system suggested by much of the literature is the unique response to short wavelengths i.e. blue and violet. A short description of those reponses follows. Violet and blue have the shortest wavelengths and according to Hilz et al.; Haig; and Peskin and Bjornstad [4-7] when these colors are used for preadaptation exposure, the dark adaptation times are larger than for any other monochromatic colors (see Fig. 4). Conversely, the longer wavelengths e.g. yellow and red have the shortest adaptation times. When low contrast targets are used (Hilz et al.) rather than the 100% contrast targets of Hecht, orange gives shorter adaptation times than red and yellow is as good as red.

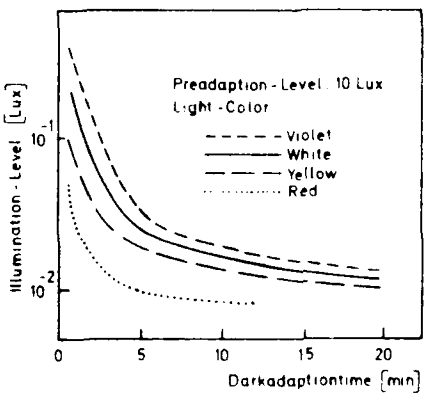

Fig. 4 : Long time darkadaptation process after preadaptation with different light colors.

In the retina of the eye are two kinds of sensors : the cones for photopic vision (day vision) and the rods for scotopic vision (nightvision). There is only one type of rod with no ability to discriminate between colors. In addition there are three types of cones which are different in color sensitivity (spectral response), namely: "blue", "green", and "red" cones. The blue cones differ from the others in that they are not located within the central area of the "fovea centralis" as are the others and they are only sensitive down to approximately 10 Lux, while the red and green cones are sensitive down to approximately 0.01 Lux. Also, there is evidence from visual experiments that the rods use the same conduction paths as the blue cones. This leads to no confusion because the blue cones become ineffective before the rods become operative. The upper threshold of rod sensitivity is about 10 Lux.

Considering the differences of the eye's response to blue light compared with other monochromatic colors and the fact darkadaptation times are worse with blue and violet light it seemed reasonable to suppose that darkadaptation time with white light might be significantly improved by filtering out only the shorter wavelegths of blue and violet. This would have the advantages of polychromatic light and none of the disadvantages of red light. The question is : Would this "filtered white light" be sufficient for obtaining adaptation times comparable to red light with the relatively lower adaptation conditions on ship bridges as compared to Hecht's laboratory conditions?

thoroughly investigated, especially by S. Hecht et al. and others (1-4). Hecht recommended the use of red light (wavelength > 600 nanometers) for ship bridges at night based on his experiments. However, the use of red light has some problems and disadvantages. First, it is monochromatic, and it prevents the use of colors for coding purposes on maps, charts, controls and displays. Secondly, practical methods of producing red light for general illumination is by filtering methods which waste up to 98 % of the light energy thereby requiring considerable increases in power for night lighting purposes. Finally, many ship personal complain of a reduction of alertness and some difficulty in keeping awake with red light.

What were the conditions in the Hecht studies under which the shortest darkadaptation times were reached with low intensity red light? In the Hecht studies absolute detection thresholds were measured using Landolt - C - rings as test objects with 100% contrast (i.e. black objects on white background). Furthermore, he used high preadaption levels of 30 Lux to about 10^6 Lux using either *white light* or *monochromatic red light*. Subjects therefore had to darkadapt over an illumination range of at least 7 and as high as 12 orders of magnitude. Are these the conditions which exist on ship bridges at night?

Based on interviews with commercial and military ship officers the following conditions prevail on shipbridges. Detection of objects at sea is normally performed by electronic aid (i.e.radar, sonar) which are normally superior to the human eye. Observers at sea need to recognize and identify objects which are normally already detected. Absolute threshold measurements with Landolt rings are relevant for detection only. Also objects at sea usually do not have 100% contrast. Contrast is frequently very low and is further degraded with optical aids. Ship control situations require that observers on a bridge at night be able to adapt nearly instantaneously. Even if the observer is fully darkadapted his ability to detect objects at sea will depend on the size and distance of the object and its contrast with the background. Identification will further depend on his experience with like objects. This means that although the lowest illumination level encountered at sea is 10^{-4} Lux the lowest practical illumination level *) in which objects could be identified with the fully dark adapted eye is about 10^{-3} Lux rather than the absolute threshold level of 3×10^{-6} tested by Hecht. Finally, no preadaptation illumination levels greater than 30 Lux can be expected to be required on ship bridges at night. Sea charts with color coding imposes the highest illumination levels from 10 Lux to 30 Lux. Most other visual tasks can be performed well at lower levels (down to 1 Lux). This means that observers on a ship bridge at night are already preadapted at much lower illumination levels than subjects in Hecht's experiments. Night observers at sea must therefore darkadapt only over an illumination range of from 3 to (in the worst case) 4.5 orders of magnitude. Clearly, the conditions in Hecht's experiments are different from those which really exist on the ship bridge at night and the magnitude of darkadaptation which is required at sea is much less and therefore shorter in time than what was required in Hecht's experiments.

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*) Because of the severe contrast condition found at sea at this level, detection would also not occur at levels below 10^{-3} Lux.

This short time drop occurs when starting from any preadaption level down to 10^{-2}. The short time threshold drop still occurs when starting at lower preadaption levels but the effect is smaller. Beyond the first 10 seconds, the detection threshold will continue to drop slowly due to chemical processes until it reaches the illumination level of the darker condition. The time required to complete this process depends on the order of magnitude between preadaption and dark adaption

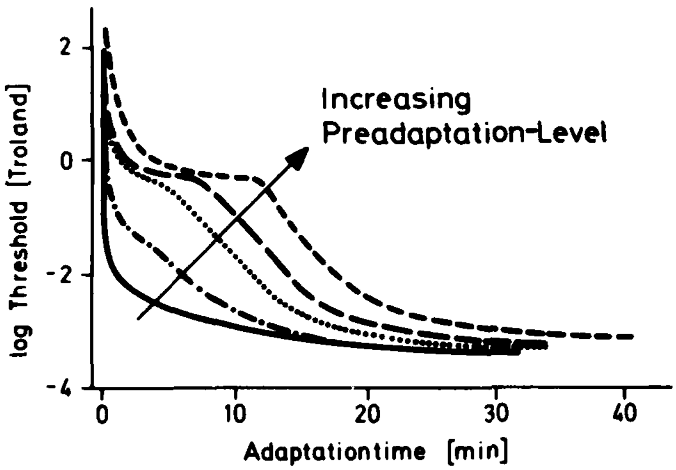

Fig 2 : The process of long time-adaptation as a result of chemical actions (parameter : preadaptation light level)

levels (see Fig. 2) and on the color of light involved (see Fig. 3). The lowest absolute threshold has been found at about 3×10^{-6} Lux. This long time chemical dark adaptation process has been

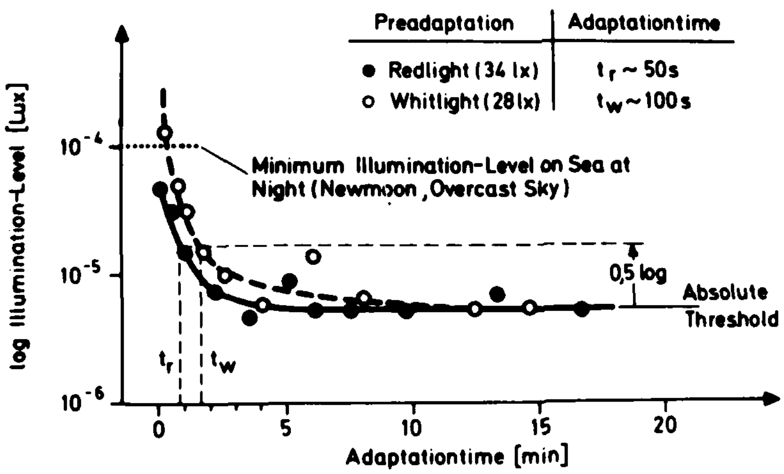

Fig 3 : The process of long time-adaptation (parameter : preadaptation lightcolor)

Adaptation level problems arise when the same observer has to look at objects of such different intensities as 10^{-4} Lux and 10 Lux. There are two types of situations which are handled differently by the eye.

In one situation, the observer views two objects, fields, or light sources simultaneously i.e. both are in his field of view. If these things are different in intensity by more than 10^{3} the eye can not detect the lower intensity source. The observer is in effect blinded by the higher intensity. This is technically known as the simultaneous-contrast or local adaptation problem. It can be solved by technical changes in illumination on the ship bridge such as adjusting illumination levels, shielding light sources etc.

In the other situation, the observer's tasks require him to view the two objects, fields or light sources sequentially. For example, comparing items on a chart at > 10 Lux with real world objects at night illuminated < 10^{-3} Lux; an order of magnitude difference greater than 10^{4}. There is little problem when going from low intensity to high intensity illumination levels since light adaptation is rather fast. But when you go from high intensity to low intensity levels you encounter dark adaptation problem.

PROCESS OF DARK ADAPTATION

Published experimental results have shown that the darkadaptation process is characterized by two different but parallel processes. One of these processes based on neural and mechanical actions is relatively short in time but has a sensitivity range of only 10^{3} to 10^{4}. The other process based on chemical actions is slow but has a large sensitivity range of 10^{15}. When the eye has previously been adapted to some light level i.e. is preadapted and is then exposed to darker conditions, its detection threshold will drop 3 or 4 orders of magnitude within the first 10 seconds as a result of neural actions (see Fig.1).

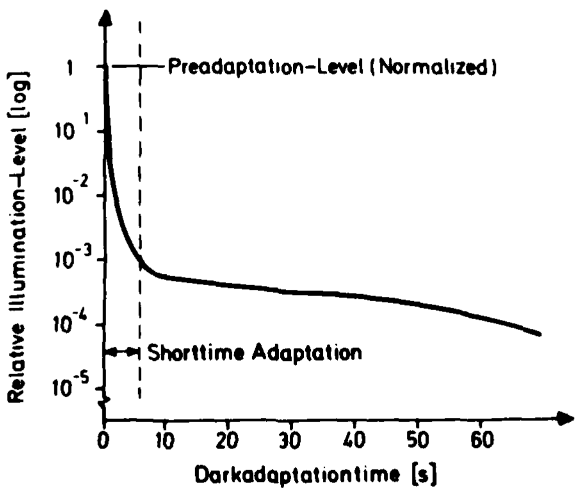

Fig 1 : The process of short time adaptation as a result of neural actions

RED OR WHITE LIGHT ON SHIP BRIDGES ?

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ABSTRACT

In this paper the limits of the human eye in relation to night vision on sea are reported. For visual tasks at night normaly red light at low brightness levels (1-10 Lux) is recommended to get shortest darkadaptation times. This decision is based on laboratory darkadaptation experiments reported in the literature. In these experiments, the subjects mostly had to detect test objects (Landolt -C- rings etc.) at the absolute vision threshold. However, visual tasks on ship bridges differ nearly in all parameters from laboratory experiments published (i.e. expected illumination levels on sea and on ship bridges, visual object and its contrast). Hence the question has to be answered, whether these results can be applied to a night vision task on ship bridges!

The process of darkadaptation as a function of the intensity and color of the previous room illumination was investigated in experimental series. The experimental parameters were : the lightcolor (white, filtered white (white without blue) and red), the brightness of room illumination (1 to 10 Lux) as well as the target contrast (100% and 13%). The visual task was comparable to that on a ship bridge at night. The results show, that the human operator is able to identify objects at practical night illumination levels within some seconds after having been exposed to brightness levels up to 3 Lux. There is no advantage of red light as compared to filtered white light with regard to the identification-time. The conclusions of these experiments are : It is not necessary to install red light with all its disadvantages in rooms like ship bridges. A "3 Lux filtered white light" illumination will meet the requirements of shortest darkadaptation time for night vision.

NIGHT ILLUMINATION PROBLEMS

Human vision is required for a large number of tasks on ship bridges, day and night. Visual tasks can be performed rather well by the human eye if illumination levels do not vary too much. During daytime when illumination levels are rather high both inside and outside the bridge there are no problems except for some low intensity phosphor-decayed targets on CRT screens (e.g. radar) which can be as low as the equivalent of 10^{-3} to 10^{-4} Lux *). At night, illumination of the outside world can be as low as 10^{-4} Lux. Because of the astronomical twilight effect it is never below 10^{-4} Lux, lower intensities are only possible indoors. On the other hand, higher intensities of light must be used for other bridge tasks including reading of other displays, printed matter, and charts. Sea charts, especially have required minimum illumination levels of from 3 to 10 Lux in order to permit the reading of additional printed color-coded data which has been added to coordinate data on the chart with data from LORAN and other modern position fixing systems.

*) The relation between luminance units and illumination units are explained in the chapter "Test objects". 1 Lux ≈ 0.1 fc

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the consistency of the man-ship reaction. The human mechanisms which are responsible for such effects are most probably factors relating to the processing of perceptual patterns. One such mechanism which has been empirically found to effect the accuracy of information processed is the organization of external stimuli. One might then speculate that specific external configurations of turn buoys lend themselves to be more accurately reconstructed in the pilot's mind such that his plan of action in controlling the ship can be executed more precisely than would be the case with other buoy configurations. More succinctly, a problem remains difficult until the environment is constructed in such a way as to lend itself to solution. Apparently differing buoy configurations given the same channel limits effect different solutions to the problem of ship control. These initial efforts on the part of the USCG and MarAd of discovering the determinants of ship control applying differing aids to navigation have launched an exciting and extremely relevant area of research involving the man-ship reaction and ship controllability.

Lastly, the research todate testifies to the importance of the display of information in the design and utilization of shipboard navigational aids. More research, however, is necessary to reduce the information variables to only those elements which are meaningfully employed in the problem solving process. Navigational systems must also be designed such that they are readily adapted to by the shiphandler. Overreliance on the adaptability of the shiphandler to the instrumentation can create serious problems in the functioning of the man-ship control loop. In short, the equipment must be designed for the man, not the man for the equipment.

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navigation aid. Of importance with respect to this instrumentation is design criteria. In the first phase of these channel experiments, digital information on the display was updated every 2 minutes whereas in the second phase, the digital information was up-dated every 30 seconds. From a cognitive processing point of view the information should be up-dated anywhere between 2 and 20 seconds since this is the span of short term memory. More concisely information which enters the system will be processed within a time span of 2 to 20 seconds[8] otherwise it will decay and be lost. Therefore, a time period for up-date of information should be established within this range in order to obtain the most proficient use of information. A rate of up-date within this range may, however, increase the workload and therefore interfere with optimal ship control. Whatever the case the issue should be further addressed by way of additional research.

Other issues concerning the amount of information to be displayed are the sensory mode and number of dimensions within that mode to be employed for transmitting the information. For example, the human viewed as an information processing system is limited in terms of the number of steps within each dimension he is capable of processing. The significant factor then is to attempt to supply the human with as few alternatives to choose from with respect to controlling the position of the vessel in restricted waters. In order to establish information criteria, one must specify a limited class of variables which are essential to ship control. Given the case of the Precise Navigation instrument, information should be filtered such that the fewest sources of variation necessary for track keeping be displayed. These sources of variation most probably would include:

- Heading
- Course made good
- Deviation left or right of track
- Speed along track in kts.
- Speed across track in feet per minute
- Distance to turn point

As our research has indicated both a digital presentation of some of these sources of variation as well as a graphic presentation elicits the most proficient performance on the part of pilots attempting to transit this restricted channel. However, the digital presentation in terms of these sources of variation may produce speed stress[9] which is defined as too much information to attend to and process in too little time. On the other hand using a graphic information display employing several visual dimensions: color, intensity, motion and size, most of these sources of variance can be processed visually and simultaneosly while a redundant alphaneumeric digital presentation can be supplied in the upper left hand corner of the display for more precise numeric information. In support of the visual graphic presentation recent studies at CAORF comparing both the digital, as well as, the graphic Precise Navigator display in the same channel have shown that track keeping is more uniform and consistent exhibiting less deviation from the reference track and fewer intersections of the reference track employing the graphic display mode.

SUMMARY & CONCLUSIONS

The results reported herein when coupled together indicate that for safe navigation of a restricted channel special consideration must be given to the configuration of buoys marking turns as well as buoy spacing in a straight legged channel. The data indicates that buoy spacing interacts significantly with channel width in effecting

- A digital display presentation of position with reference to an ideal track. This display presents nautical miles to turn point, feet off track (right or left), speed along track and feet per minute across track (see Figure 15).

NM to Turn Point	xx.xx
Ft off Track	xxxx R (or L)
Kts along Track	xx.xx
Ft/M across Track	xxxx R (or L)

Figure 15. Digital Precise Navigation Alphanumeric Display

The analysis of performance indicated that cut-off corner buoys provided for the most successful performance. The turn point buoys again were insufficient; however, they did reduce learning time to successfully transit the channel as compared to the single turn point buoy of the prior experiment. Regarding the configuration of the turn point buoys, the pilots did not use the start buoy and pull-out buoy as was expected. The start buoy was used for setting up as opposed to being used for a point of initiation for the turn. There was also a lack of consistency in leaving this type of turn configuration, the pilots demonstrated high variability in pulling out which produced problems in track keeping for the following leg.

With the cut-off corner buoys the pilots allowed themselves more maneuvering room than in the turn point buoy configuration. Behavior was much more consistent and uniform for approach and pull-out of turns with this cut-off corner configuration. Turns were executed with less rate of turn and a more fluid approach was achieved allowing for greater control on the following leg.

Mid-leg channel buoys in all conditions improved position determination and assisted in control of the ship for setting up position for the coming turn.

The use of the digital precise navigation instrument allowed for the most controllability in transit of the channel, producing the best overall performance and consistency in track keeping. Apparently, the pilot can maintain the position of the vessel within the channel limits using this instrument in the absence of any fixed environmental

- Cut-off corner buoys as configured in Figure 13.
- Cut-off corner buoys with additional mid-leg buoys for *each leg as shown in Figure 14.*

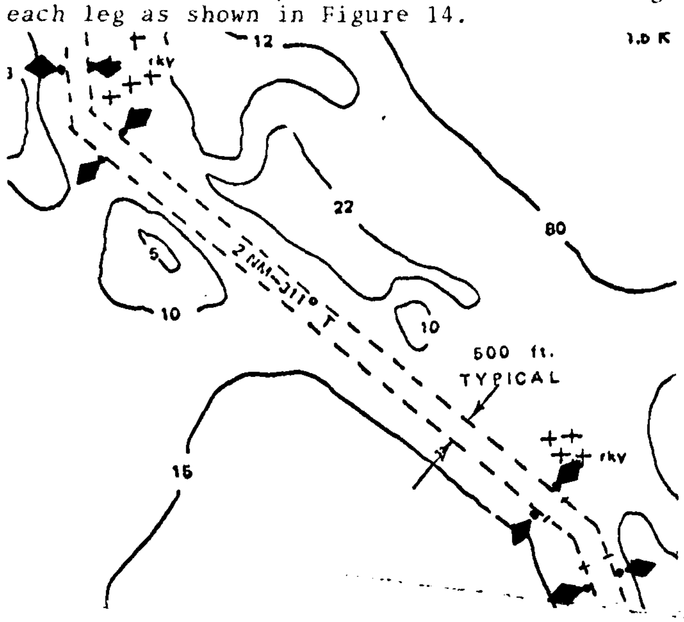

Figure 13. Cut-off Corners Configuration

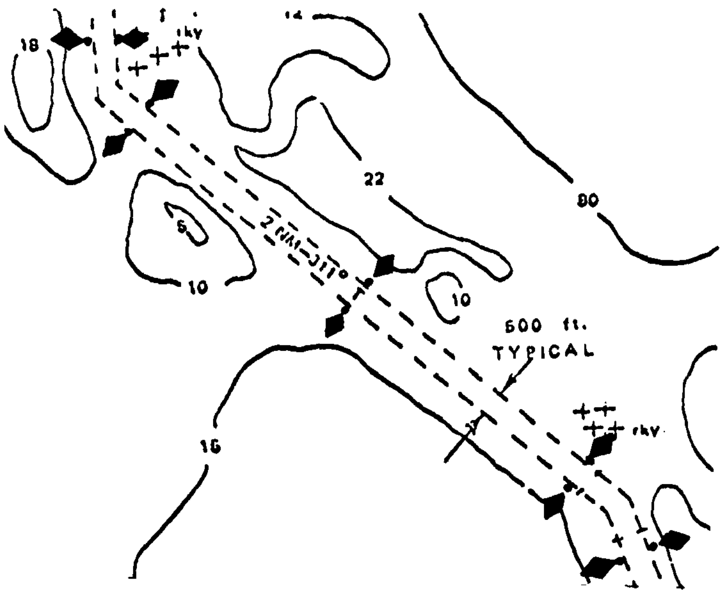

Figure 14. Cut-off Corners plus Mid-Leg Gates Buoy Configuration

- Turn point buoys as configured in Figure 11.
- Turn point buoys with the addition of mid-leg gate buoys for each leg of the channel as shown in Figure 12.

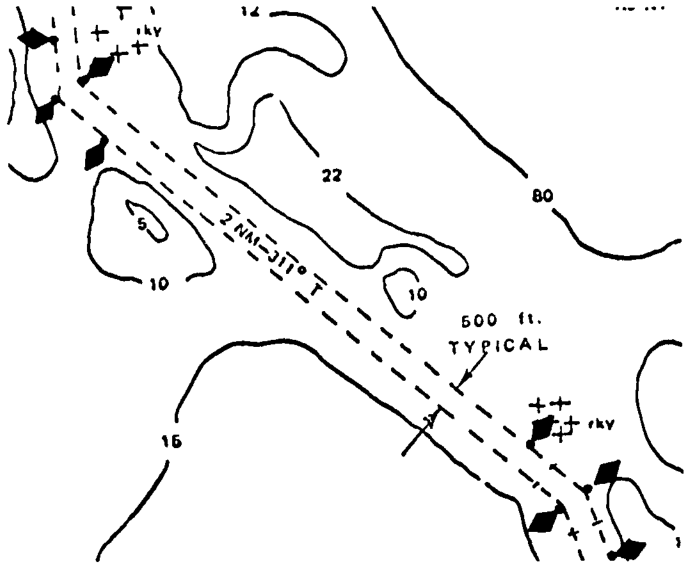

Figure 11. Turn Point Buoy Configuration

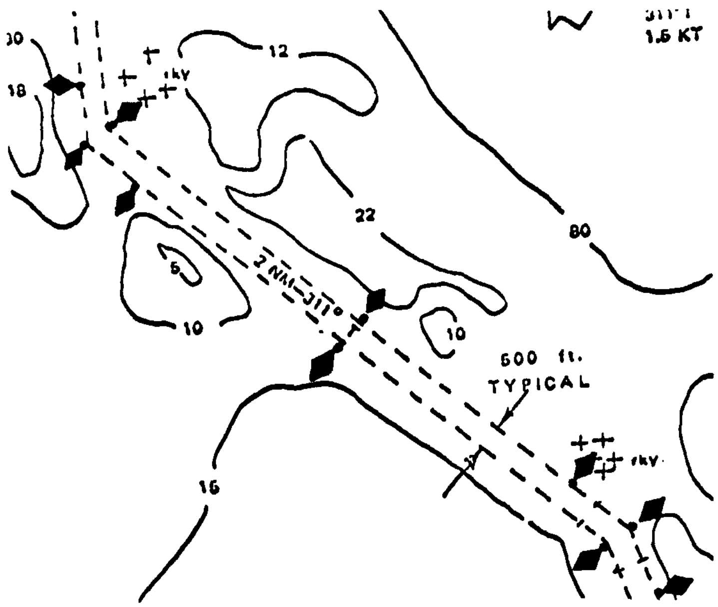

Figure 12. Turn Point Buoy plus Mid-Leg Gate Buoy Configuration

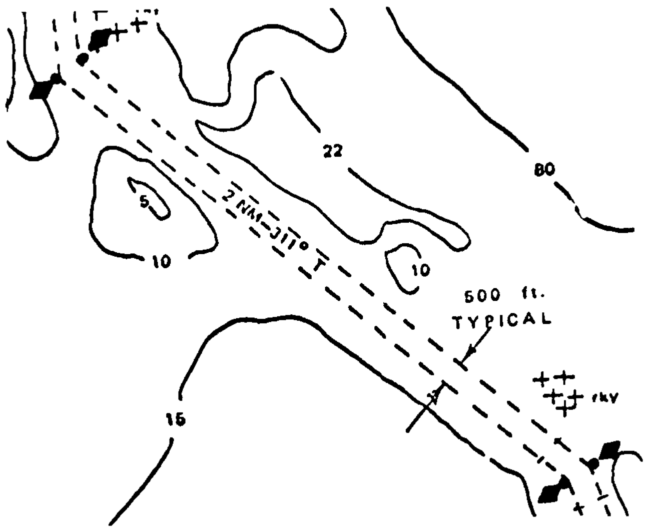

Figure 9. Buoy Pairs

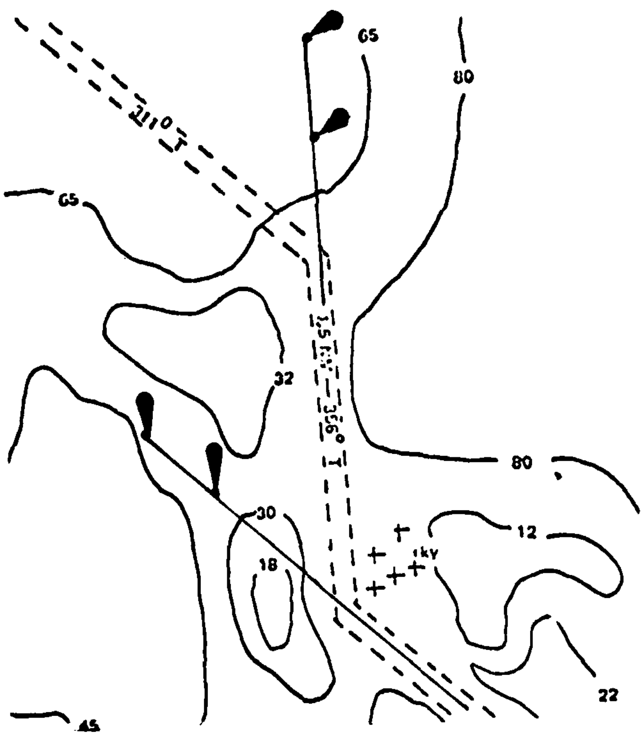

Figure 10. Ranges

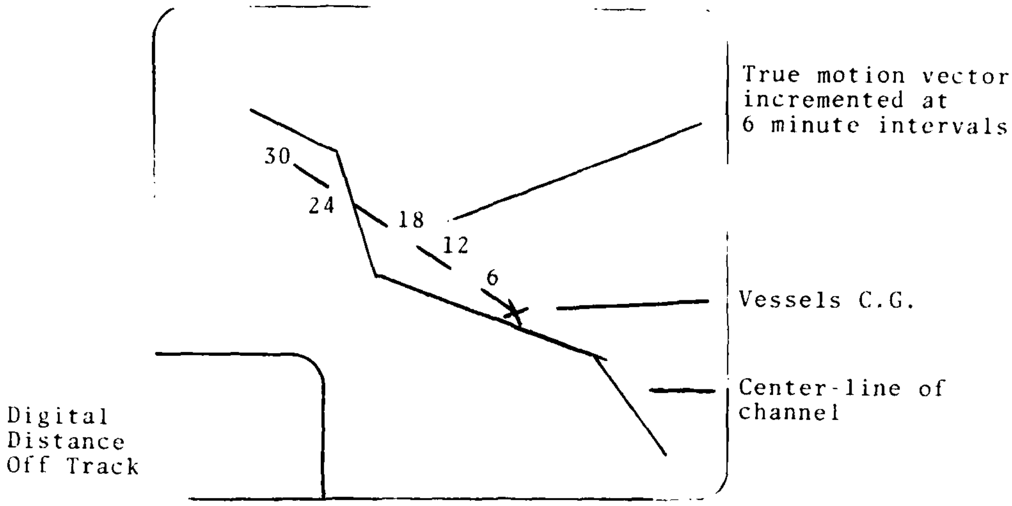

Figure 7. Vessel Condition as Provided by Precise Navigator

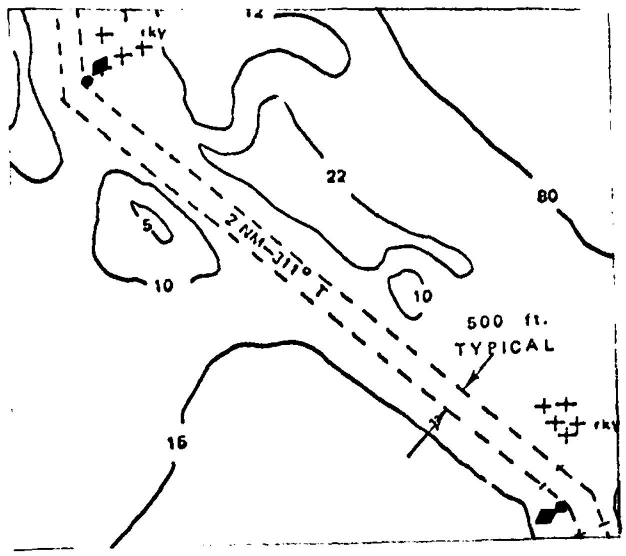

Figure 8. Corner Buoy Configuration

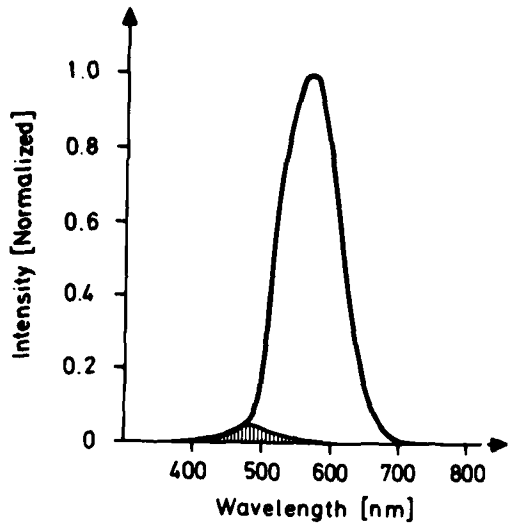

Fig 5: Photometric spectral distribution of white light; the hatched area represents the blue part filtered out by the 485 nm edge filter.

so that the spectral power distribution of the incandescent bulbs is also held constant. The different illumination levels of 1, 3, and 10 Lux were generated by altering the voltage applied.

Test Objects

Black silhuettes of a ship in five positions on a white background were used as test objects. The various target aspects used were as follows:

1. left 90° (running left perpendicular to the line of sight)
2. left 45° (running left at a 45° angle towards the observer)
3. straight 0° (running towards or away in the line of sight)
4. right 45° (running right at a 45° angle towards the observer)
5. right 90° (running right perpendicular to the line of sight)

Fig 6 (next page) shows the test objects in the five different directions. The contrast of the ship against the sky (background) is varied in two steps: 100% and 13%. The test objects correspond to the following real visual situation: A ship (76 m long, 6m wide, and 15m high) at a distance of 3 kilometers is observed with binoculars (magnification factor 6). Test objects were projected onto a screen by a programmable slide projector and viewed by subjects at a distance of 80 cm. The intensity of the white background was varied in 10 steps between 10^{-2} and 3.16×10^{-6} cd/m^2 *) for 100% contrast and between 3.16×10^{0} and 10^{-4} cd/m^2 for 13% contrast targets. The intensity was achieved by using neutral filter combinations in the projector beam. Test objects with a refectionfactor of <0.01 (black ship contours) against a white background with a reflection factor of 1.0 illuminated with 1 Lux have luminances of < 0.003 cd/m^2 and 0.3 cd/m^2 respectively. This relation results from the following equation:

$$\text{object luminance } [cd/m^2] = \frac{1}{\pi} \times \text{ reflection factor} \times \text{ illumination level } [\text{Lux}]$$

*) 1 $cd/m^2 \approx$ 0.3 fL

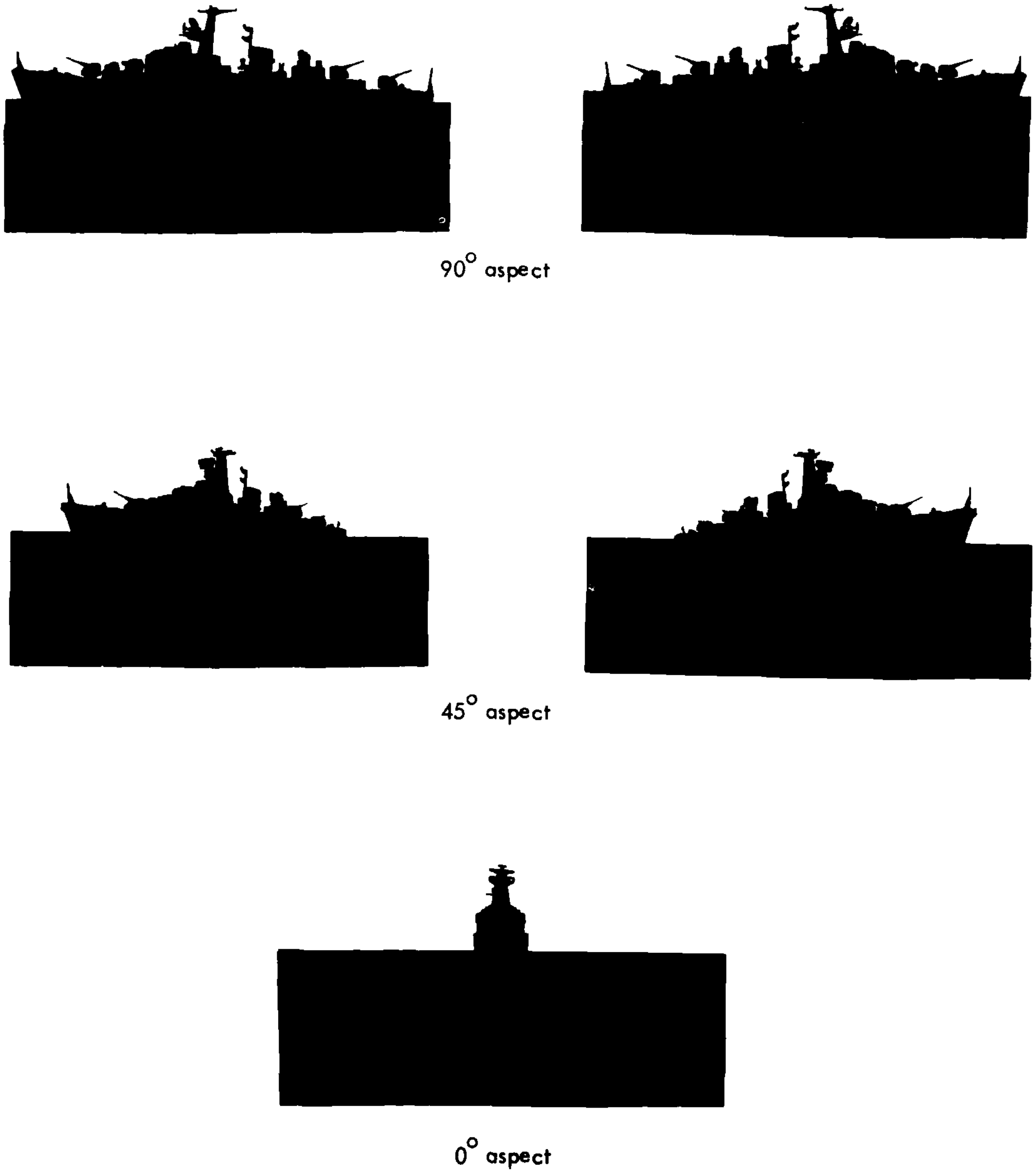

Fig 6: The five different test objects used in the experiment (i.e. ship silhouettes under different aspects)

In our experiments background luminance of test objects was tested with a Pritchard Photometer.

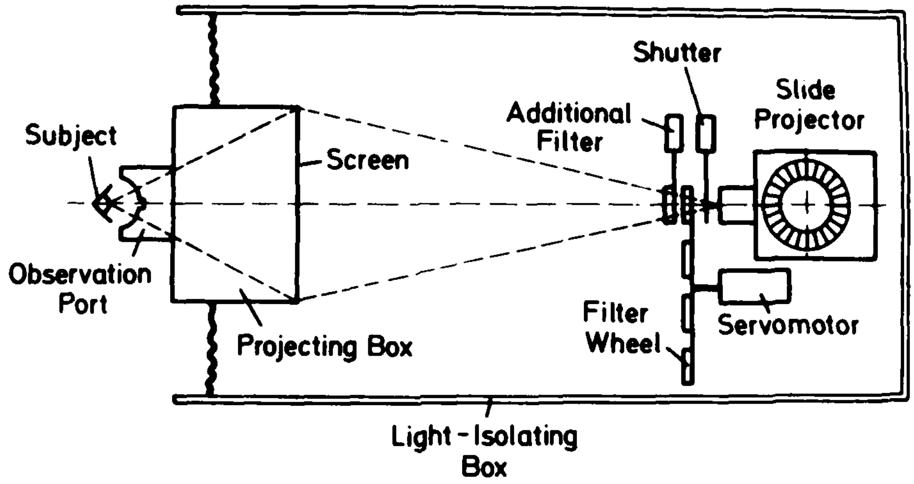

Fig 7: Experimental arrangement (schematically)

Fig 7 schematically shows the experimental arrangement. This whole arrangement was light isolated and positioned in a large box. On one side the subject can see the screen through an observation-tube. The box was placed in an isolated testroom where the subjects are exposed to one of the different pread aptation light conditions, described earlier.

Subjects

For selection of subjects the following conditions had to be met:

- They had to be color normal i.e. not color blind
- Their accommodation focus distance at low illumination levels must be between 70 and 90 cm because of the 80 cm viewing distance in the experiment.
- Subjects with eyeglasses were only permitted if he could press his face to the observation tube so as to light-isolate the tube.
- The subjects had to be familiar with dark adaptation experiments because of viewing strategies varied in the dark (moving of eyes and peripheral viewing) to avoid local retinal adaptations between targets and background which creates a simultaneous contrast problem. Without this training, subjects will have identification times that are to long.
- Some of the subjects should have experiences with actual night viewing tasks at sea.

On total, 18 subjects were tested in these experimental series, 5 of them were ship officers. The ship officers met all five conditions but the other subjects only met the first four criteria.

Experimental Procedure

One or two subjects were tested concurently using the same preadaptation condition (light color and intensity). During one series of experimental runs subjects remained in the testroom. Subjects first adapt for at least 45 minutes to the preadaptation light condition. After one test object and the corresponding neutral filter combination have been adjusted with a closed shutter, the subject who is looking through the observation tube opens the shutter by a toggle switch. When the object had been identified, the subject closed the shutter and removed the eyes from the tube. Subjects were instructed not to look at the lamps at close range or into dark zones of the room. The open-time of the shutter was electronically measured as identification time. The verbal answer is recorded by the experimenter together with identification time and the experimental parameter. If they cannot identify the objects within 3 minutes the test is stopped with the result "not identified". After a preadaptation time of at least one minute for each subject the next test followed. The two subjects tested look through the observation tube by turns during one experimental session. Each subject had his own random sequence of test objects. During one session 50 objects had to be identified. Each subject was used for at least four sessions. The following experimental results were based on about 2000 measurements.

EXPERIMENTAL RESULTS

The experimental results are graphically presented in figures 8 to 10. Identification time in seconds is represented on the x-axis whereas the adaptation illumination level is logarithmically scaled on the y-axis.

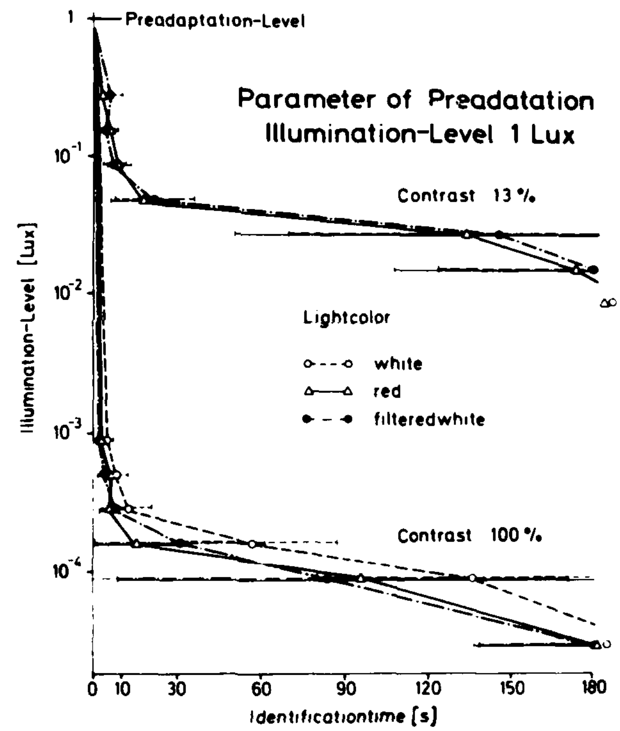

Fig 8: Process of darkadaptation for all subjects after 1 Lux preadaptation (Parameters: contrast 13% and 100%; light color red, white, filtered white)

Effect of Preadaptation Light Color

In figure 8, it can be seen that about the same adaptation time is required for subjects exposed to 1 Lux of either red or filtered white light. This is especially clear with low contrast (i.e. 13%) targets. Even with targets of 100% contrast there are no significant adaptation time differences between red and filtered white light down to just above 10^{-4} Lux, almost the lowest possible illumination levels found at sea. On the other hand, adaptation time of 1 Lux white preadaptation light are double the time of the other time tested down to the same lowest viewing level.

However, the adaptation times for all subjects regardless of the preadaptation light color used down to the lowest practical condition at night, namely, an illumination level of 10^{-3} Lux, are all below 10 seconds with no statistically significant differences between them.

Effect of Preadaptation Level

In figures 8, 9, and 10, the results for preadaptation light levels of 1, 3, and 10 Lux respectively are presented. Identification times do not vary as a function of preadaptation level down to practical illumination levels of 10^{-3}. Differences occur only below this level. As might

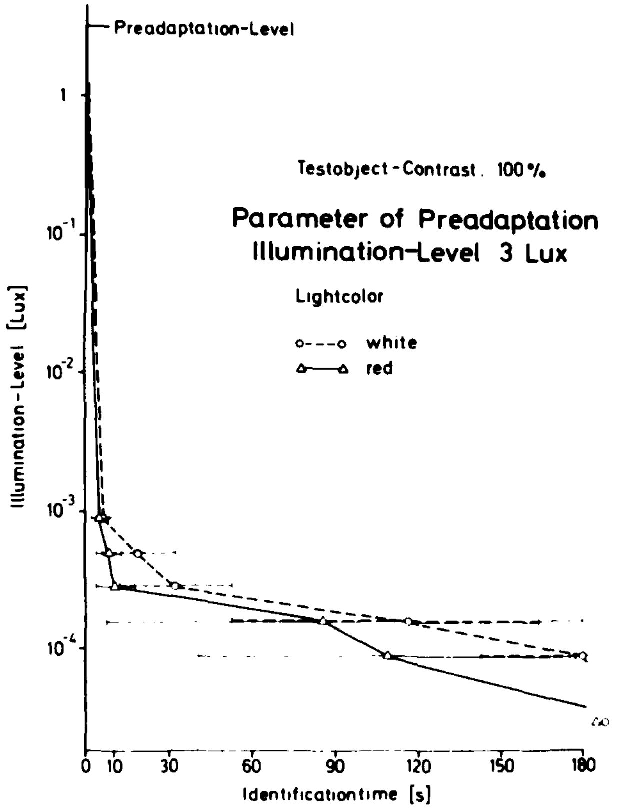

Fig 9: Process of darkadaptation for all subjects after 3 Lux preadaptation (Parameters: contrast 100%; light color red and white)

expected dark adaptation times down to $10^{-3.5}$ increase with increases in preadaptation level. For example, adaptation times for both red and white preadaptation light colors for 10 Lux are about 3.5 times the adaptation durations of 1 Lux.

Effect of Contrast

In the first 10 seconds, test objects with low contrast (i.e. 13%) were identified at an illumination level about 3.5 orders of magnitude higher than the level at which test objects with 100% contrast were identified (see figure 8). The fact that more light is required for identification of low contrast than for high contrast objects is true regardless of preadaptation light color.

SUMMARY AND CONCLUSIONS

The main problem for night observers at sea is the darkadaptation problem when going from relatively high intensity to low intensity levels. On a result of experimental studies, Hecht and other have recommended the use of red light on ship bridges as a preadaptation light source. However, a number of problems are encountered when using red light. Therefore, a comparison of conditions in Hecht's experiments were made with actual conditions found on ship bridges at night. The comparison shows that the highest illumination levels on the bridge are much lower and the lowest illumination levels on the sea are much higher than those tested by Hecht. Consequently, the range of adaptation required at sea is only from 3 to 4.5 orders of magnitude rather than

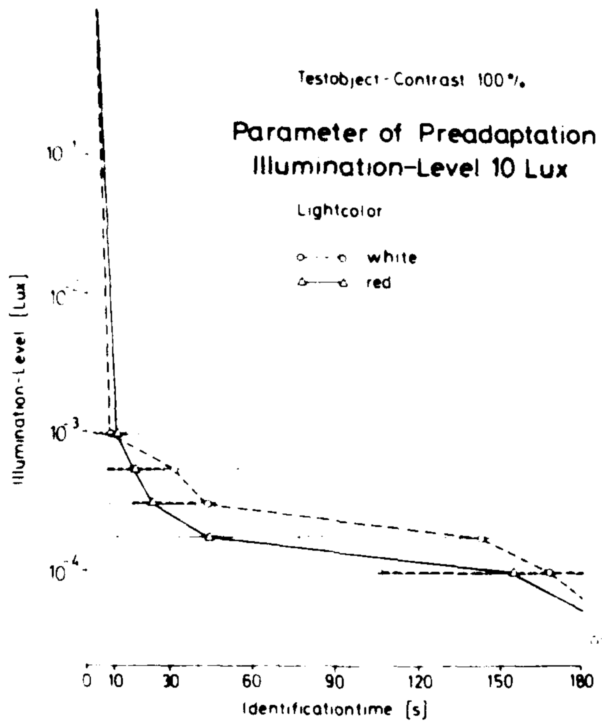

Fig 10: Process of darkadaptation for all subjects after 10 Lux preadaptation (Parameters: contrast 100%; light color red and white)

the 7 to 12 ord ers of magnitude in Hecht's studies. A survey of the literature has supplied a number of hints that darkadaptation requirements for observer at sea can best be satisfied by using relatively moderate levels of white or filtered white (blue filtered out) light instead of red. The most important of these hints is the fact that the first 3.5 orders of magnitude in darkadaptation is accomplished by fast acting neural processes in the human visual system which operates indepently of light color.

The question of preadaptation light color only affects the infrequently occuring last half order of magnitude of adaptation possible at sea for the seldom seen high contrast targets. For this small part of the problem various studies indicate that adaptation times are not lowest with red light when low contrast targets found at sea are need instead of the 100% contrast Landolt-C-rings used by Hecht. Additionally, it is clear from the literature that blue and violet preadaptation light has the worst effect on adaptation times.

As a consequence of these considerations an experiment was designed and run to determin how low levels of white, filtered white and red light compare in identification time for sea targets under simulated sea viewing conditions. No differences were found in the first 10 seconds of adaptation time during which targets of high and low contrast were identified down to practical illumination levels of 10^{-3} and 10^{-1} Lux respectively.

For the infrequently occuring cases where adaptation is required to lower illumination levels obtainable after the first 10 seconds by chemical processes in the human eye, it was found that there were no significant differences between red and filtered white preadaptation light sources. When subjects were preadapted to white light, darkadaptation times were significantly longer than either of the other two colors. Since the only differences between white and filtered white light is the presence or absence of short wavelengths, such as blue and violet, our results confirm the negative effect of the blue light on the darkadaptation process.

Based on the results of this experiment, the information available in the research literature, the viewing conditions found on ship bridges and the type of targets found at sea at night it is recommended that low levels (about 3 Lux) of filtered white light be used for night visual tasks abroad vessels at sea.

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SHIPS PILOTAGE IN BRITAIN - PAST, PRESENT AND FUTURE

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ABSTRACT

This paper is part-descriptive, part-empirical and part-speculative, concentrating on the theme of ship's pilotage. A brief outline of the history of pilotage in Britain serves as a prelude to a summarised account of a recent comprehensive 'human factors' survey of the stress and problems of the professional pilot. The description of the study emphasises ship handling and navigation from the pilot's frame of reference, especially in relation to the control of large ships like the 'Supertanker'. The paper then develops ideas for problem-solving with particular reference to the training of pilots. The British ship-handling simulator will be considered in the general context of its usefulness as a training and research tool, and its relevance for pilotage training discussed.

Historical Perspective

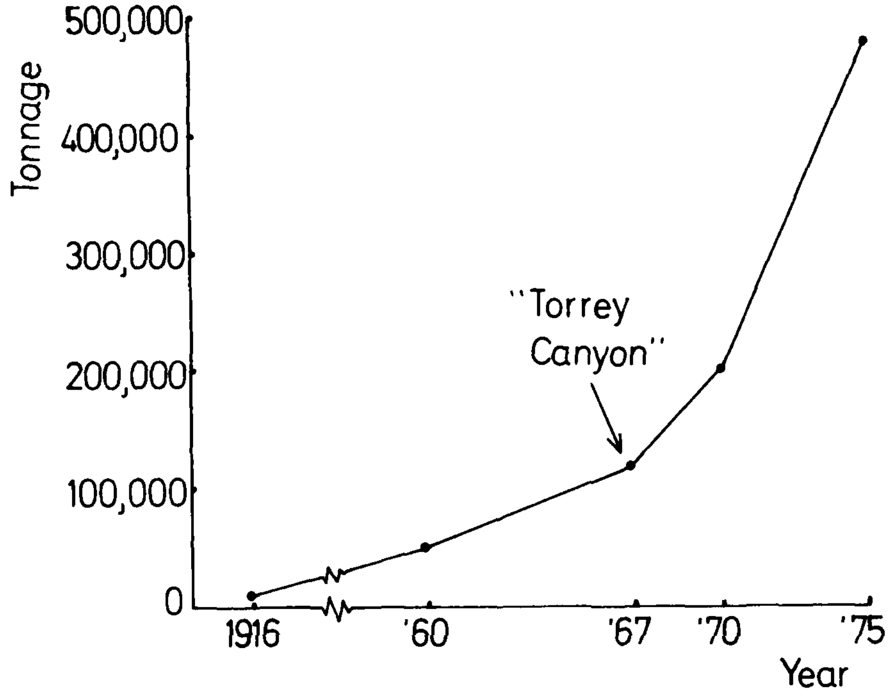
The British pilotage service to shipping is an ancient institution; Trinity House (London), for example, received its Royal Charter from Henry VIII in the 16th Century. But the historical antecedents of the research project outlined below are much more recent in origin. In the last half century pilots have witnessed many forms of change.

Commercial changes have been large in their impact, both locally and nationally. In common with other European maritime nations the effects of a post-war trade boom up to the early 1960s was felt in the service when the demand for pilotage was probably greater than the capacity of the service to meet that demand comfortably. Pilotage manning levels caught up but the pendulum has swung the other way and only very recently does trade seem to be picking up after the world recession due to the events following the 1973 Middle East military conflict.

Over the years since the end of World War II there has been a steady increase in the mean tonnage (NRT) per act of pilotage for both British and foreign movements combined, and since the early part of [illegible] the proportion of pilotage acts on foreign ships has steadily increased (DoTI Report, [1]). The fall in the total number of pilotage acts is a direct result of economic and trade fluctuations and technological changes resulting in fewer but bigger ships. Although it is impossible to measure the effects of such changes on pilots' health and well-being, these factors have to be borne in mind, particularly with reference to the pilot from the older generation who will have endured the effects of wartime combat as a Merchant Mariner and then the burden of the heavy workload of the post-war decade. Finally, he would have had to adjust to a new class of large ship technologically very different from its predecessors.

Large container ships and bulk carriers are commonplace these days, with cargo being carried in larger single units, but it is the giant oil tanker - the 'Supertanker' - typically 200,000 tons (dwt) and above, which is the most dramatic of technological changes in modern shipping. The growth in ship size has been exponential. In the past 50 years the largest ships afloat have increased nearly 100-fold from about 6,000 tons to 500,000 tons (dwt). These very large ships present special pilotage problems, especially in marginal conditions of weather and port layout and limited underkeel clearance. There is also the problem of 'slow speed dynamics' for pilotage skill: i.e. the long delays in the ship's response to pilotage inputs. (Brigham [2]).

There are grave pollution risks and large potential damage costs associated with accidents with these ships. It is against this historical backcloth that the scene for this research project is set. Although, with the exception of the Panama Canal, the ship's pilot is not legally responsible for the ship he pilots, he nonetheless plays an important part in her safe handling and navigation in pilotage waters.



Data:

Year:	1916	1960	1967	1970	1975
Tonnage:	5,800	50,000	120,000 ↑ "Torrey Canyon"	200,000	476,000 ↑ Japanese

Figure 1. Increase in Ship Size

Increasingly concerned at the apparently high rate of fatal heart attacks amongst their members, in 1966 the London Channel Pilots Committee initiated discussions with medical experts. Dr. J. Slack of the Medical Research Council's Clinical Genetics Unit, who had made a study of risk factors in coronary heart disease in the general population, did a comparison of coronary mortality in Trinity House (London) pilots with the general population. The results were disturbing and confirmed the pilots' fears. They showed, in addition, that pilots in the younger age groups were particularly prone to cardiovascular disease and the overall figures were much worse than was at first anticipated.

It was strongly recommended, therefore, to set up an independent scientific investigation to look into the entire field of pilotage workload since the latter factor was hypothesised to be an important contributor to the problem. Scientists at the London School of Hygiene's Centenary Institute of Occupational Medicine were brought into the picture under the guidance of their director, Professor Richard Schilling. Some small-scale studies were done but finances necessary for the proposed full-scale study were not available. Drs. Taylor and Serjean studied pilots' working hours and highlighted their irregularity and the uncertainties of the job. Dr. Harrington conducted a retrospective study of records covering a 13-year period of London District pilots. Although the study was inconclusive and the number of deaths was small it indicated yet again that the younger men were experiencing an excessive mortality from heart disease, (Harrington,[3]). Harrington extended his study to Manchester and Liverpool pilots who had entered the service through the apprenticeship method, and their mortality experience was considered to be more like that of the general population than the London pilots, but again the problem of small numbers occurred. Harrington suggested several contributing risk factors including previous Merchant Navy experience and mental stress at work. Unfortunately, comparative figures from the Merchant Navy were difficult to find. The exception is Otterland's [(4)] study of Swedish seafarers, in which he showed that officers experienced a higher death rate from heart disease than ratings.

In 1972, Dr. Kwie of the London School of Hygiene (Kwie,[5]) was asked to investigate Humber pilots where it was also feared a high prevalence of heart disease existed. He also came up against the problem of small numbers for a proper statistical study, but concluded that no excessive mortality from coronary disease was seen in the Humber pilots. The average age of the Humber pilots was younger by about 5 years at time of appointment than their London District counterparts, and some had been recruited from the apprenticeship scheme.

Soon afterwards, and quite independently, the Research Division of the National Ports Council (NPC) became interested in pilotage problems as a result of discussions held with pilots at the annual NPC-sponsored pilotage seminar at the University of Wales Institute for Science & Technology. Because of long-standing research collaboration between the NPC and The Department of Occupational Psychology of Birkbeck College, the latter was invited to submit a research proposal to the NPC to investigate stress problems of ships' pilots, with special reference to handling very large ships. At the same time, a separate comprehensive proposal came from the London School of Hygiene. Consequently, the proposals from the two sister school of London University were amalgamated into a single proposal. After several working party meetings and addressing several pilotage groups, money was secured and sufficient goodwill to mount an interdisciplinary 'human factors' study in October 1975, some nine years after those early initiatives by Channel pilots. Because of the historical factors outlined above, special emphasis has been given in planning this project to the problem of cardiovascular disease in pilots and its early detection.

The Research Project Outlined

The work was supported by various pilotage groups, the National Ports Council, the General Council of British Shipping, through the Association of Pilotage Authorities in the U.K. (APAUK),and the Department of Industry (Ship and Marine Technology Requirements Board.)

The initiative for the research came mainly from the pilots themselves, and the reasons for the study included: the dissatisfaction expressed by pilots with their conditions of work and their concern for the safe guidance of ships in our waterways; and some medical findings suggestive of job-related heart disease among pilots. The aims of the rssearch were to assess pilotage activities for stress problems, especially in relation to workload, and to make recommendations for the alleviation of such problems as were found to exist. This was with a view to the longer term improvement of pilots' satisfaction with working conditions in keeping with the maintenance of high standards of professional service; and to contributing to the safe handling of ships in our ports and other confined waterways.

There were several inter-linking sub-components of the project developed to further these aims, the general methodology emanating from a crude conceptual model of forces hypothesised to be acting on the pilot to produce strain (see Figure 2). A medical screening study has been done on a sample of Trinity House (London) pilots to establish a health profile for comparative purposes, and to furnish baseline values for the London Ship Workload Studies. Some of these men were studied at work on ships by means of environmental and physiological monitoring. These ship studies quantified the contributions made by pilotage workload, under various conditions, to individual strain. A ship workload feasibility study was conducted in the summer of 1976 at a major U.K. oil port, and a workload measurement package was evolved for the main studies which were conducted in the London District. A feasibility study on the collection and analysis of records of pilot deaths and sickness from the war years up to date was completed. The advantage of such a study is that it would take account of the effects on pilotage health of events which have changed over the time period covered, such as the frequency and type of shipping. Because of costs involved and the variability in standards of record-keeping between districts it was decided that a full-scale study of records could not be done and a 2-year part-retrospective and part-prospective study covering the time-scale of the project was put in its place. Other components of the project were: questionnaire studies on how pilots perceive their life and work, and diary studies for studying pilot activities in 'real time' over monthly time periods to highlight work-rest and standby patterns and their implications for sleep, leisure, diet and other life experiences of pilots.

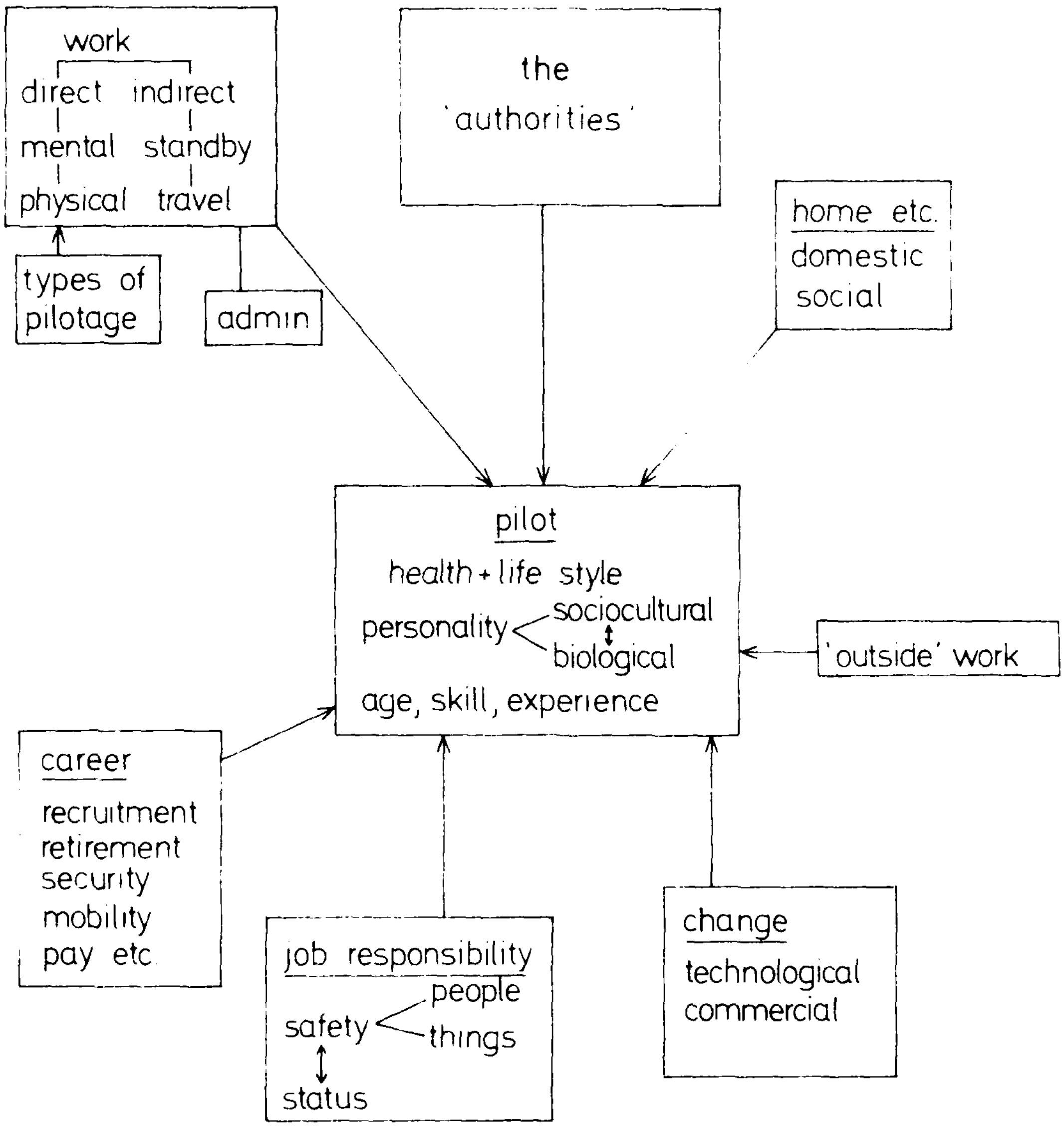


Figure 2. Hypothetical Sources of Strain

For historical reasons, much of the study was concentrated in the London region, and resources limited the scope of the investigation. If findings were to be representative of U.K. pilotage in general then means, such as questionnaires and diaries, had to be found allowing full participation by the total pilotage population. Two main principles underlay this research: that participation was voluntary and that all individual results were entirely confidential to the research team.

Some Selected Findings

In the model in Figure 1 we differentiate two types of workload. By 'direct workload' we mean both physical acts of boarding and disembarking and the mental loading on the pilot when actually piloting. 'Indirect workload', on the other hand, refers to other aspects of the job such as travelling to and from the ship and waiting on standby at home or at the pilot station (both the shore-based and the floating variety). The major criterion used has been heart-rate which we found to be a useful and sensitive measure.

We have looked at the magnitude of the workload and the health implications by comparing our data on pilots with that from other studies on similar responsible occupational groups. It was planned to study pilots on both routine and more difficult pilotage assignments and in a variety of weather conditions. In fact conditions turned out to be unusually clement. We must assume, therefore, that our data are biased toward the less stressful end of the spectrum.

In summary we found that generally the pilotage of a 'very large crude carrier' is more demanding than pilotage of other ships, but there were many cases where even much smaller ships produced very high heart rates in seemingly healthy men, implying that the environmental context for pilotage such as manoeuvring into a berth or dock in tidal and wind conditions, is very important.

Pilotage acts were divided into 'short-haul' of about 2 hours and less and longer haul. The former produced greater average heart-rates because the kind of pilotage done was mainly of the ship-manoeuvring rather than the sea-navigation kind that typified the longer haul. Both boarding and disembarking periods also produced high heart-rates, and in general the 'resting pulse' of the pilot waiting to ship was consistently lower than the direct workload pulse. It was not uncommon to find sustained average heart-rates well over 100 b.p.m. whilst piloting and on occasions peaks of 150 and above could be identified. Heart-rate increased as the task became more demanding, such as manoeuvring a ship in physically-restricted water, berthing or mooring, or avoiding a collision.

We examined the longer pilotage acts for diurnal effects since these acts were dominated by night work, but none were found. A separate small-scale fatigue study showed that the pilots on night pilotage had normal diurnal rhythms. The average peak for long hauls was 143 b.p.m., compared with 127 b.p.m. for short acts. In the literature on other responsible jobs sustained average heart-rates, we noticed, tend to be lower than our long-haul pilots. Melton and his colleagues (6), for example, report average values between 82 and 92 b.p.m. for air traffic controllers taken in a range of American airports including some with quite demanding traffic loads. And what little evidence there is also suggests that pilotage makes greater demands overall on the ship's pilot than long distance flying does on where I is the identity matrix, "-1" represents the matrix inverse operation, and elements r_{ij} of R are the mean number of times the process enters Cell j given the process starts in Cell i.

The next and final step in the comparison of ship response patterns is to compare subject controlled ship response for each display to each of the optimal ship responses. MT(I) is used to denote the mean number of times Cell I is entered before the process enters the absorbing cell (21). Comparison is made with the sum of the squared differences of the cell mean entries (MT(I)). The comparison is made of the MT in Cells 1-5 and 7-11, deemed the critical region cells since they represent a situation where a CPA violation (less than 2 mile CPA) is projected. The Wilcoxon matched-pair signed-ranks test was used for the comparison. Subject performing in each set of two displays provided the matched pairs. Performances with the three displays were compared two at a time.

Candidate OMAC

A set of candidate OMAC's were developed based on the instructions and operation rules given to the subject, and the Maritime International Rules of the Road. Factors that could be included in candidate OMAC are:

$$C = \sum_{i=1}^{N} (A + \sum_{j=1}^{M} K_j B \left\{ f(2 - CPA_j) / TCPA_j \right\}$$

where $A + B = 1$, $A, B \geq 0$

- i = one minute interval number
- j = activated contact number
- K_j = 1 if a CPA violation is projected for contact j, otherwise $K_j = 0$
- CPA_j and $TCPA_j$ are the CPA and TCPA for contact j
- N is the number of one minute intervals
- M is the number of contacts
- Function f is given in Figure 2

The first term is the transit time weighted by A. The second term is a penalty of a CPA violation weighted by B and the inverse of TCPA.

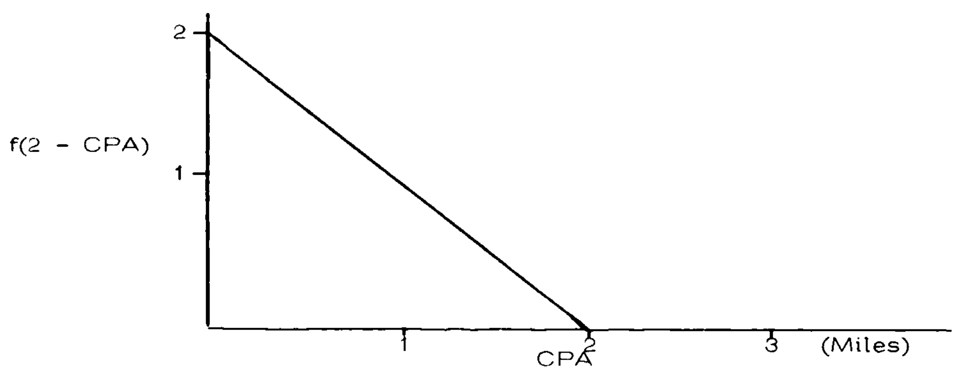


Figure 2. f Functions.

Transition Matrix

Cell transition patterns characterize the OOD's contact avoidance and transit maneuvering. Likewise, transition patterns representing a group of OOD's (such as those using a particular display) can be used to characterize the group maneuvering patterns.

Cell transitions are represented by transition probabilities since cell sequences are not fixed - even those representing performance of an individual performer. The transition pattern from a given cell, say Cell i, is recorded in the associated row of a 21 by 21 transition matrix. Probability (P_{ij}) is the probability of transferring to Cell j from Cell i on each time interval. In the experiment, data was sampled every minute so that the probabilities are associated with the indicated transfer in each one minute interval.

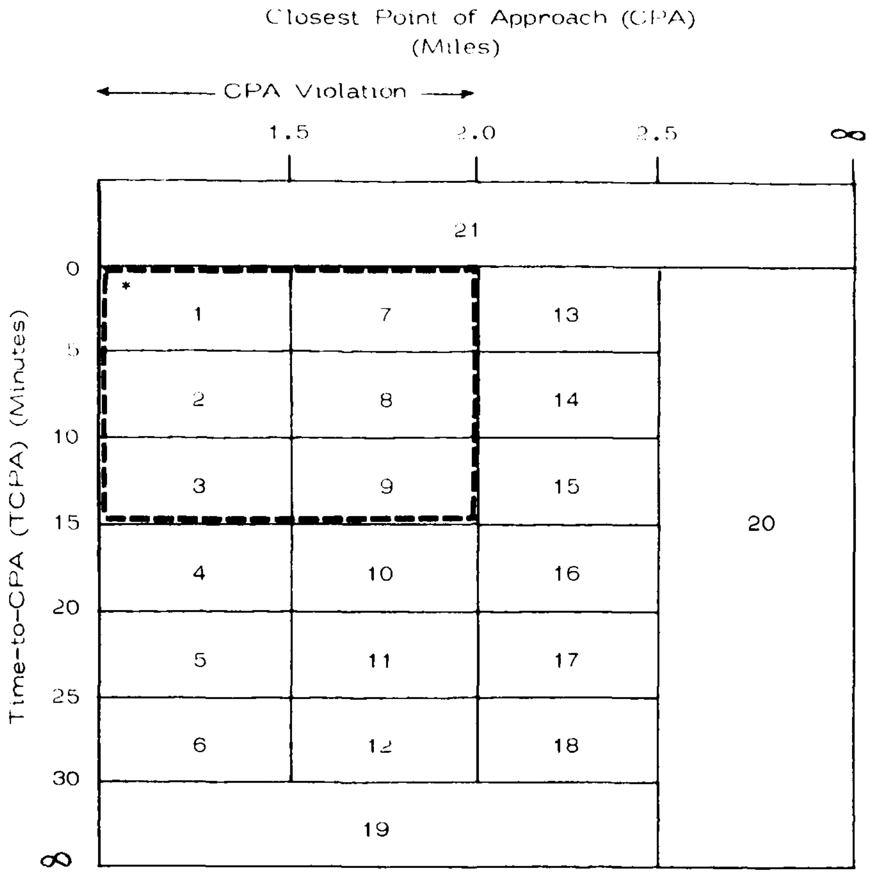
Comparison of Ship Response Patterns

Considerable analysis of ship maneuvering patterns can be accomplished by inspection of the transition matrix probabilities. For example, an entry in Cell 6 corresponds to a projected CPA violation in 25 - 30 minutes. The transition 6-11 (Cell 6 to Cell 11) is better than the transition 6 - 5 and the transition 6 - 16 is better than either of the other two. Thus, transition patterns characterize the ship maneuvering patterns of a subject or group of subjects. Examination of transition probabilities provides a way of evaluating performance and comparing performance with the different displays.

One difficulty in the quantitative evaluation of performance, using transition probabilities alone, is that transition from a given cell is not weighted by the probability the cell is "used." For example, with one treatment (one display type), transition from Cell 3 may not be as good (a high probability of transfer to a cell that does not project a CPA violation) as that of another treatment. But the probability of the existence of the condition corresponding to Cell 3 may be so small that transitions from Cell 3 may be of little consequence. A method for solving this problem is described in the next paragraph after introduction of a required concept.

Once a contact is passed, where distance from contact is increasing, there is little likelihood that the ship will maneuver so as to approach that contact again. Assuming that is true, Cell 21 can be treated as an absorbing cell, i.e., the probability of leaving the cell after the cell is entered is zero. With that assumption, the transition matrix can be analyzed as an absorbing Markov Process (Kemeny & Snell, 1960). This means that the process is considered as starting in any cell (but especially Cells 19 and 20) and transferring to a series of other cells ending in Cell 21. An entry may return to a given cell in that process but once entering Cell 21, it remains there. The analysis of interest is the calculation of the mean number of times each cell will be entered before entering the absorbing state given the starting cell. This provides the desired measure of cell usage. Calculation of the measure requires formulation of a matrix Q which is identical to the transition matrix P except that Row 21 and Column 21 (corresponding to the absorbing cell) have been removed. The desired measure is given by matrix R (a 20 x 20 matrix):

$$R = (I - Q)^{-1}$$



*Cells 1, 2, 3 and 7, 8, 9 are designated critical cells where a CPA violation is projected to occur within 15 minutes.

Figure 1. Definitions of CPA/TCPA Cells.

As an aid to understanding how the entries in the CPA/TCPA matrix change as a function of ship and contact position changes, consider the following typical situations. If the ship speed and course remain constant over several time intervals, cell conditions change to decrease TCPA. For example, an entry in Cell 6 would "transfer" to Cell 5 because of the elapsed time.

If ship course or speed is changed by the OOD as a contact avoidance or transiting maneuver, other cell transitions occur. As an example, an entry in Cell 6 identifies a condition where, unless ship (or contact) course or speed is modified, the ships will pass within 4,000 yards in 30 minutes. If no action is taken, the entry in Cell 6 will transfer to Cell 5 because of the elapsed time. In order to avoid a contact violation (passing within 4,000 yards), it is necessary that the OOD command a change of ship speed or course such that the entries are transferred to a cell without a projected violation.

allow the subject to select display functions, to input trial course and speed, and to direct course and speed change commands to an individual representing the Helmsman.

The task of the subject OOD's is to visualize or calculate the possible courses from present ship position to the objective point. Then, by taking into account the contact positions and velocities and by utilizing the various display functions available, he is to direct the ship to the objective position. The instructions read to the subject prior to each trial are "the objectives during the run are to be at the rendezvous at the end of the 90 minute period, to pass clear of all contacts (if possible by more than 4,000 yards), to obey the Rules of the Road, and to observe economy of operation."

Performance with three types of displays is of interest. The three are: "OLD system," "PACS system," and RVV system." The OLD system is essentially a conventional radar display where the center of the screen is the position of own ship and the relative position of contacts are shown as blips.

PACS, a new display, provides a number of different display functions which are selectable by the subject. PACS (possible area of collision) is the name of the function and the name of the display system providing that function. In PACS, LIST is available on the left-hand CRT. Also, the subject can select the new display function PACS or true velocity vector modes on the center CRT. With the PACS mode, the display provides the locus of collision points for each contact for all own ship courses. Since this requires projection of future own ship and contact positions, the display aids the subject in selecting a new course. With the true velocity vector mode, velocity vectors are superimposed on the own ship and the contact "blips" to show the predicted position of all the ships at a future time selected by the operator.

Finally, another new display termed "RVV system" includes LIST plus relative velocity vectors. These are vectors superimposed on contact blips that indicate the relative position of each contact with respect to own ship at a future time selected by the operator.

Contact Avoidance Performance Measurement - CPA/TCPA Matrix

According to the instructions provided to the operator, he is to direct the ship to the objective point within the prescribed time while avoiding contacts by at least 4,000 yards if possible. Analysis of how he accomplishes the task requires a method of dividing the problem situation into categories so that the performance in each category can be examined. The selected method uses a CPA/TCPA matrix (CPA is closest point of approach and TCPA is time to CPA) as shown in Figure 1. Cells in the matrix correspond to intervals of CPA and TCPA. At each time interval, the state of the ship (position, speed, course) and state of each contact specify a cell condition. For N contacts there are N cell conditions. For example, Cell 1 corresponds to a projected CPA of from 0 to 1.5 miles which is projected to occur within 0 to 5 minutes. Cell 21 represents the situation where the CPA has already occurred, i.e., range to the contact is increasing. Projected CPA violations (passing within 4,000 yards (2 miles)) are identified by entries in Cells 1 through 12 and Cell 19.

The investigation reported here used data collected during a series of experiments in which a subject acting as an Officer-of-the-Deck (OOD) controlled a simulated ship in a simulated environment. His task was to direct a ship transit from the initial point to the terminal point within a pre-specified time interval while avoiding simulated contacts along the way. The experiment, using equipment known as the Surface Ship Bridge Console System (Gawitt/Beary), was run by personnel of NSRDC, Annapolis, Maryland, for purposes other than this research program. The data from that experiment was used in the research reported here.

METHOD

The objectives of the research were accomplished with four analyses which are described in Connelly 1976. A brief description of each analysis is presented here. In addition, a description of the performance measures and OMAC factors used is included.

Analysis I was to analyze performance data from the experiment using summary measures. Its purpose was to determine if performance is actually different with different displays. Analysis II was also a performance study but used measures that detect control actions that lead to critical conditions (near collisions). In addition, Analysis II provides the performance measure required to compare synthesized (optimal) ship responses to the subject ship responses obtained from the experiment. This comparison is required to identify apparent OMAC from a set of candidate OMAC. Analysis III was an initial test of OMAC where optimal ship responses were developed in a one-contact problem. The purpose of the analysis is to establish a set of factors to be included in OMAC for test in Analysis IV. Once a set of OMAC factors was established, the apparent OMAC was determined in Analysis IV. Composite performance data representing performance of subjects working with a particular display are compared to performance data from the set of OMAC. From that comparison, the OMAC apparently used by the operators with each type of display are identified.

Description of the Manual Control Task

The subject acting as an Officer of the Deck (OOD) commands the ship course and speed required to transit the simulated ship from the initial position to the final position while avoiding each simulated contact (other ship) encountered. The distance between the initial and final positions is approximately 30 miles and the time allotted for the transit is 90 minutes.

The subject sits in front of a simulator console which has three computer driven CRT displays and a number of control switches. The CRT display directly in front of the subject is the main display and provides visual information about the location of (own) ship and contacts. The configuration of that display varies with the particular display function simulated, and thus, is an experimental variable. The CRT display on the subject's left provides a list of contact information such as location, speed, heading, and closest point of approach (CPA). This display is termed "LIST". The display on the subject's right provides data on ship course and speed. It can also provide data on "trial" course and speed which the subject may input for evaluating decision command changes. There are a number of control switches which

3. Does the design of the system controls and displays affect the "apparent OMAC"?

4. How can the "apparent OMAC" be used to evaluate alternative displays?

Questions 1 and 2 refer to processes that are inverse to each other. Question 1 asks: given the operator's control actions, can we determine his OMAC? And Question 2 asks: given OMAC, can we predict the operator's control action in each problem situation? Optimal control theory provides a means to relate OMAC to the control actions which optimize the OMAC although the solution may not be unique. For example, there may be more than one OMAC optimized by a given set of control actions.

Question 3 refers to the determination of the effect of display and control equipment on the OMAC. To understand the significance of this problem, it is necessary to distinguish between OMAC and the objectives of the control system combined with any instructions or standard operating rules that may be presented to the operator. The later, the system objective and instructions, provide overall guidance. Examples are "direct the ship to the objective point and arrive there in one hour," and "remain in channel." In order to satisfy these instructions, the operator will develop OMAC to evaluate the system response and select appropriate actions on a moment-to-moment basis. We should note that the OMAC may or may not be totally consistent with the instructions provided to the operator. He may make trade-offs which may lead to violations of the operation rules.

An answer to Question 4 would give the designer some way of selecting among alternative designs based on the performance expected from each.

The identification of the OMAC and the development of methods of converting OMAC to control actions in each problem situation provides a new way of representing (modeling) the human operator. There are several potential benefits of such a model. One is that OMAC may be predictable over a wide range of problems and problem situations and, thus, may be used to predict human response in those situations. A human response model using OMAC (i.e., representing the human operator by the criteria he tends to optimize) contrasts with the input/output (stimulus/response) model. This latter type of model is extensively used to represent human response but it suffers from several difficulties among which are .- they are problem specific and they are generally limited to representing linear control policies.

Research Objectives

One objective of the research was to develop a design tool consisting of the apparent OMAC used by operators in performing their tasks. This required development of a method for identifying the apparent OMAC from experimental data and development of a method for applying an OMAC to predict operator control actions and the resultant ship response.

A secondary objective was to develop a performance measure for ship control and with this measure evaluate the effect of different displays on contact avoidance performance.

CRITERIA OPTIMIZED BY COLLISION AVOIDANCE STRATEGIES*

by Edward M. Connelly
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ABSTRACT

In existing man-machine systems, the human operator is typically presented a predesigned display and he must adapt his control techniques in an attempt to optimize overall system performance. Ultimate performance achieved may not rise to the designer's expectation or to the operator's capability because the design process does not account for the operator's adaptability. In this research program, ship control performance of the Officer of the Deck (OOD) was observed and analyzed in a series of simulator experiments involving ship transit and obstacle avoidance. Three types of displays were included in the analysis. OOD control rules, and measures and criteria which describe the control technique used, as well as the criteria employed in controlling the ship, were derived from the individual performance data. The effect of display type on the measures and criteria which were apparently optimized by the subjects was determined.

INTRODUCTION

The designer of a man-machine system typically performs his design task with knowledge of system objectives, human factors principles, and display and control requirements. However, it is the human operator who adapts his control rule (his input/output control characteristics) so that the overall system response satisfies (to the degree possible) his performance criteria. The performance that is actually achieved will be obtained in cooperation with a system that has a good system design - and in spite of a system having a poor design.

The above argument suggests that the designer should have available as a design tool a means for estimating the operator's performance criteria and his control actions. The designer would like to know which design features support performance and which features degrade performance. The need for such knowledge suggests several research questions:

1. How can the "apparent Operator's Measure and Criteria (OMAC)" be determined: (The term "apparent OMAC" is used to mean those measures and criteria that are optimized by the operator's observed control actions.)

2. How can the "apparent OMAC" be used to predict operator control actions in specific problem situations?

*This research was supported by the Engineering Psychology Programs, Office of Naval Research.

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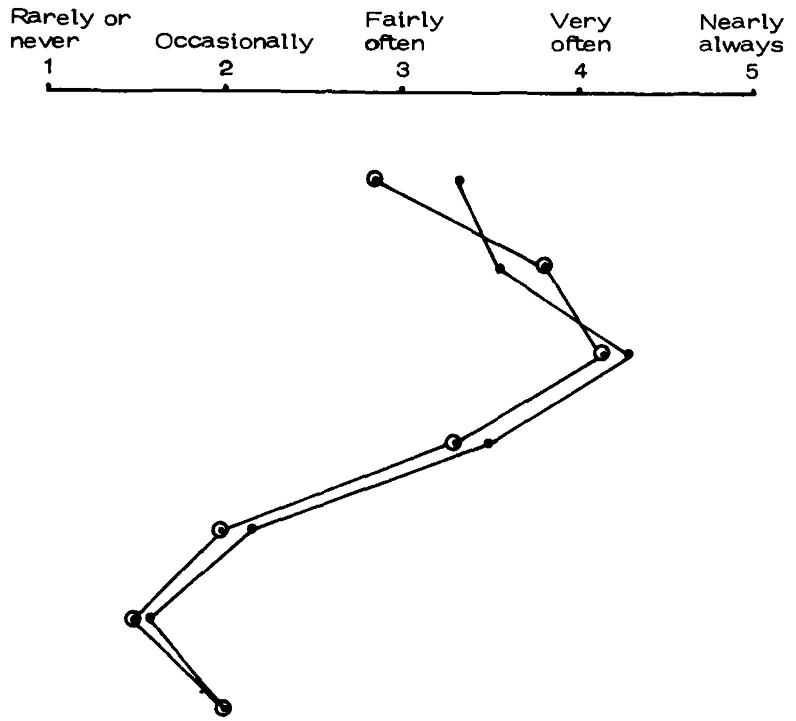
Training is a particularly interesting field of study for pilotage, and the theme cannot be treated independently of the issue about modes of entry to the profession; i.e. the apprenticeship mode or direct entry from the sea with a Master's certificate. Identifying training needs requires an adequate analysis of the skills, knowledge and attitudes important for doing the job well, and this will depend on what qualities the trainee brings with him partly as a function of his mode of entry and partly his own personal aptitude and potential.

There are various conceivable levels and types of training; it can take the form of basic training, 'refresher' courses, 're-orientation' and 'up-dating' courses, and advanced training. It may go beyond the purely technical (both theoretical and practical) to include other perhaps less obvious considerations such as training in interpersonal skills, man-management and knowledge of human nature. The pilot is by reputation, and to some extent by role and function, an independent and self-reliant individual. Perhaps he needs to be in his job where independence of judgement is prized and necessary. But team-work is a process that takes place on the bridge and is important for the efficient and safe conduct of the ship. The pilot is a member of that team, if only a temporary one, and his communications with others, especially his relationship with the Master, will affect his job satisfaction and the quality of the decision-making during the riskiest part of the ship's voyage.

The new British ship simulator could be investigated as a possible supplementary training tool for pilots. An informal 'sitting next to Nellie' scheme operates at present for direct entry pilots who spend a period of between 3 to 6 months watching another man pilot the ship. The simulator is intended for both research and training purposes, but primarily as a training tool for mariners navigating in pilotage waters, providing a variety of exercises for ships up to 500,000 tons. It is an aid to ship-handling training for all bridge crew, including pilots, except for the most experienced VLCC pilot. Plans are afoot to assess the realism of the simulator, and its suitability for basic pilot training as a supplement to present schemes may be a component of such a validation programme. We need to determine precisely what the simulator is capable of doing and how well it does it. It may be possible, for example, to compare exercises in the simulator against experience with their parallels 'on the job', using a variety of performance and other measures. We need to know how psychologically real the experience is and how far there is a positive transfer of training from the simulator to the job. The initial training time of the novice pilot may be reduced, and 'risky' ship manoeuvres may be practised safely on the simulator. The team-dynamics and the qualities of good seamanship can be investigated and the suitability of the simulator for team training assessed. Furthermore, the most common criticism of simulators, especially aircraft simulators, is that they fail to create the stress of the real job. We are interested, therefore, to measure the stress-invoking capacity of the simulator and its consequences for safe performance and good decision-making.



	Average Values: Population Survey •	Average Values: Medical Sample ⊙
1. Participation	3.3	2.8
2. Clarity	3.6	3.8
3. Cohesion	4.3	4.2
4. Utilization	3.5	3.3
5. Training	2.2	2.0
6. Support	1.7	1.6
7. Conflict	2.0	2.0

Figure 4. Profiles of Role Stress

hazards, levels of responsibility and the unpredictable, irregular nature of the work; factors which make greater demands on certain types of individual.

Ship manoeuvring in close quarters conditions perhaps favours the unflappable person who keeps calm and cool and does not remain worried and tense long after the pilotage. Long-haul pilotage, however, may favour a 'biological type' who is well able to tolerate irregular working hours. In our recommendations, therefore, we urge a three-pronged attack on this problem: careful psycho-medical assessment of the new recruit; the provision of an occupational medical unit with an advisory and counselling as well as screening function; and the provision of suitable shore jobs somewhere in the system for the 'grounded pilot' who is no longer suitable for practical pilotage. An alternative or supplement to the latter would be an ill-health pension scheme or loss of licence insurance cover.

In Figure 4 profiles of role stress are given for the population of pilots as a whole and for the London medical sample. There are two factors which stand out as worthy of attention: the generally felt lack of support from other groupings in the system such as ports and pilotage authorities and ship-owners and their representatives; and the lack of training opportunities both on and off the job. The quality of liaison and communication between pilots and authorities varies between districts and generally the trends are gradually moving in the direction of better links between groups as a result of hard work and determined efforts on both sides. But there is still room for improvement.

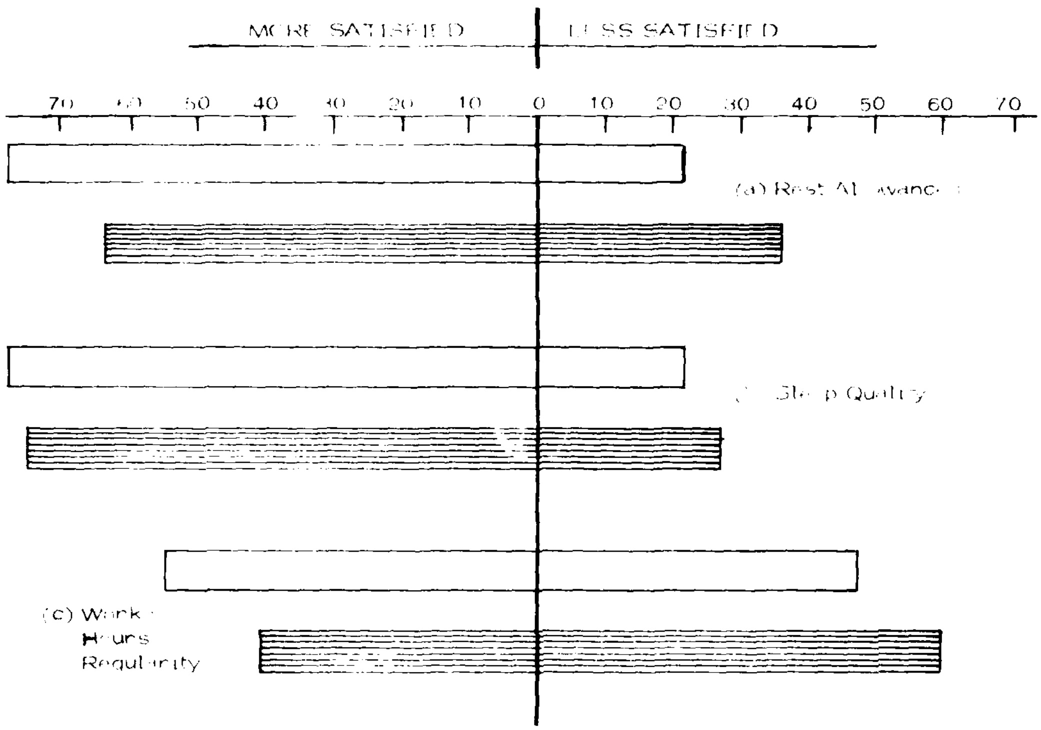
Some Recommendations

Certain recommendations follow from the study and it is difficult to judge at this stage what impact they will have on a profession which is in a state of flux as a result of the government's S.C.O.P. report(7). The S.C.O.P. enquiry was intended to lead to a new Parliamentary bill on pilotage and the eventual up-dating of the 1913 Statute, but many points raised are contentious and so far Parliamentary time has not been made available for the debate. For example, a major S.C.O.P. recommendation was the setting up of a Central Pilotage Board and such a Board could have implemented the acceptable recommendations of this study. Now there is a strong force to retain the jurisdiction and complete autonomy of local pilotage authorities with the possible institution of a national standard for certain matters, such as pilot recruitment and training. One thing that is clear in many minds is that the shipping industry, all sides of it, needs to take a long hard look at itself and get up-to-date for social as well as economic reasons. Criteria of health and well-being of personnel in service are being increasingly recognised as important, along with the time-honoured concern for cost-efficiency of transportation of goods by sea. Environmental pollution costs borne by those innocent of the perpetration of such damage is also a less tolerable factor these days.

In the questionnaire we asked pilots what they thought about their future prospects. Advancing technology and automation, on ship and shore, we thought, might affect pilots' feelings of satisfaction with their jobs. Problems raised by some pilots include feelings of insecurity about the future; the older pilots are unhappy about pensions and retirement schemes, whilst the younger men are bothered by the unstable income base and the insecurity associated with the fluctuations in economic prosperity of the port, scope for transfer between districts being severely restricted.

However, most thought that it was 100% likely that the skills and expertise of the pilot would be needed in the short term (say 5 years from now), and even in the longer term of 20 years hence. They were, on the other hand, less optimistic about a good future for their port: only about 50% likely, they said. They feel the latter is largely in the hands of port operators and managers and dependent on the attitudes of organised dock labour. Even in the majority of pilots who see themselves as indispensible links in the safety chain there are doubts and uncertainties about their future locally, and nationally depending on government legislation, Common Market policy, and other political pressures, as well as technological changes of one kind or the other.

We also looked very closely in our study at those pilots who seemed to be less adapted to pilotage. We do not mean to infer that such pilots are less competent in their jobs; indeed there is a strong suggestion that they are especially conscientious and responsible in their attitudes to their work. Rather do we mean emotionally and physically less adapted to the way of life. Such pilot[illegible]y suffer more anxiety and less self-confidence than their peers, or have excessive fatigue and sleeping difficulties. They report poor job and life satisfaction and more conflict between the job and home life. Factors in the job we think are responsible include the physical



	More Satisfied %		Less Satisfied %	
	Population Survey	Medical Sample	Population Survey	Medical Sample
(a) Rest Allowance	78	64	22	36
(b) Sleep Quality	78	73	22	27
(c) Work-Hours Regularity	53	41	47	59

Population Survey
Medical Sample

Figure 3. Percentage Dissatisfied With Quality Of Rest

the airline pilot.

Although the longer act of ship's pilotage produced generally lower heart-rates, other stresses arise which are to do with prolonged and sustained vigilance and concentration, often in the nighttime. This is compounded by the problem, a complex one, of pilots working irregular hours on unpredictable schedules, as happens in the London district. These factors tax an individual's energy and resources. The pilots do indeed subjectively assess these longer acts as more fatiguing. We found, not surprisingly, that these long-haul sea pilots were much more critical of the ship and her crew. These acts of pilotage would typically last 6 or more hours and the indirect workload factor, the waiting and travelling associated with that particular assignment, was many times longer. The return journey home having left the piloted ship is often an irksome experience for a tired pilot and usually takes place in awkward unsocial hours.

Pilotage is very much affected by local or regional factors. Pilots' fortunes are tied to the economic success or otherwise of the local port. Glasgow declined as a port with the running down of the ship-building industry. But in the Sixties, Milford Haven metamorphised from a small fishing port into a major oil terminal for the reception of oil from the Middle East. More recently in North East Scotland, the ports have boomed with the advent of North Sea oil. The harbour and estuarial structures, and tidal factors, also have a significant bearing on local pilotage. Broadly speaking, the systems or patterns of working fall into two types: the more predictable watch system and the less stable simple alphabetic turn roster characterizing the long-haul pilotage in the London district.

It is this latter kind of work system which raises so many complaints among pilots (and questions for pilots' health), but is so intangible a factor to measure and assess in an objective and scientific way. The questionnaire study demonstrated clear-cut differences in responses on some psychological strain variables between groups of pilots from the different working systems. Pilots on stations operating a more stabilised watch system suffer less fatigue. They are more satisfied with their work schedule and working conditions and more satisfied with their rest allowances and the regularity of their working hours. They also feel their work less often interferes with their eating habits.

In Figure 3 the impact of these work schedule factors on pilots' satisfaction with the quality of their rest is depicted, with the London medical sample again showing consistently lower levels. The latter also reported that work interfered more often with their sleep and eating habits, and they more often report taking hypnotics and alcohol to aid sleeping. One difficulty with this comparison, however, is that London pilots have a higher average age than the rest and there is evidence in the literature that it is the older worker who is less able to cope with shiftwork and the strain of irregular working hours. The diary study was useful because it highlighted these wide disparities between pilotage districts associated with different systems of working. From the questionnaires the job factors producing the biggest problems for pilots were: uncertainty, frustration and then physical hazard, in that order.

A computer search was conducted to identify the candidate OMAC parameters (A,B) producing optimal ship response similar to those produced by subjects in the experiment. It was found that the theoretically produced ship responses (i.e., optimal ship responses) were considerably different from those produced by the subjects. The difference was that the theoretically produced ship response corrected ship course or speed for potential collisions much earlier and at a greater range than did the subjects. This implies that the subjects were using additional criteria which somehow limited early corrections.

In order to mimic the subject's OMAC, a purview function was combined with the criterion function C. With purview of range X, the optimal ship response was determined (i.e., the response that minimizes function C) by considering only the contacts within range X from own ship. Contacts outside range X were reglected. If subsequent motion of the ships caused a contact move within range X, then the contact was considered in the synthesis of the optimal ship response. Of course, purview range X was not initially known and had to be determined along with values of weighting parameters A and B.

With this augmented criteria, where A, B, and X are parameters, the optimal ship responses produced were similar to the ship responses produced by the subject OOD's. Comparison of this response using the performance measure MT, described previously, permitted identification of OMAC (i.e., parameter values for A, B, and X) for subjects using each display type.

CONCLUSIONS

Analysis results show that performance differences between OLD and PACS, and RVV and PACS displays are significant at the α = 0.10 level. Summary measures which reveal this performance difference are time-to-CPA and distance travelled. Results confirm that time-to-CPA is an important measure since with it significant differences in performance are shown. Analysis results also reveal the nature of the performance differences. From these results it is concluded not only that there are significant differences in performance with different displays, but also that performance measures which detect responses leading to a critical condition (a collision) are more sensitive than summary measures of the critical conditions themselves.

Analysis results reveal that models of human operators controlling ships must include a purview factor. The purview factor used here was a radius within which a contact is considered. The model ignores contacts outside that radius. The purview function is required to represent all performance, i.e., without regard to display type.

Analysis of OMAC parameters representing performance obtained with each display type show that the values of A and B do not change as a function of display. Apparently criteria used by subjects is not influenced by display type. But the purview value (X) does not change with display type and the change in purview explains the change in performance with different displays. Results suggest that for the contact density of the experiment problem, PACS can be rated as at least 12.5 mile displays and that OLD and RVV are 9.6 mile displays.

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FFG-7 CLASS PROPULSION CONTROLS - DESIGN AND DYNAMIC PERFORMANCE

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ABSTRACT

This paper describes the design and performance of the main propulsion controls developed for the FFG-7 Class gas turbine-controllable pitch propeller propulsion system. The programmed (automated) controls for this system are configured so that the throttle and propeller pitch commands are generated by a special purpose digital processor with firmware. This type of system is advantageous since relatively complex control logic and computational routines can be readily incorporated.

Dynamic simulation techniques were applied extensively in the design of the program to be incorporated in the processor firmware. This paper discusses dynamic simulations and provides descriptions of the major control features incorporated in the final design. Among these features are temperature compensated open loop power control, closed loop speed control, open loop nonlinear acceleration rate limits, control strategies for extreme and low speed maneuvers, engine transfer transition routines, and parallel automatic and manual control.

Comparisons between simulations and measured trial performance are also presented.

INTRODUCTION

The automation of the FFG-7 Class propulsion controls utilized recent digital control technology, with a design which was evolved using all digital simulation of the combined control, propulsion and ship systems dynamic performance. Automatic or programmed control was implemented in processor read only memory (ROM) or firmware. This type of implementation provided the precision, capacity and speed needed to achieve flexible, preferred performance in a variety of control modes while assuring the reliability and safety of the ship and propulsion system. The technique of experimentation and verification by simulation was applied throughout the design effort. This paper describes the design and gives dynamic performance as predicted and achieved during sea trials.

The FFG-7 shown in Figure (1) is driven by a single screw all gas turbine-controllable pitch propeller propulsion system. The U.S. Navy propulsion system specification for the FFG-7 contained a number of basic requirements for control system design. Automated or programmed single lever propulsion control was required at the Ship Control Console located in the pilothouse and at the Propulsion Control Console in the Central Control Station. The single lever control (SLC) was to provide control inputs to programmed control so that linear change of the lever position would cause approximately a linear change of ship speed. The control programs were to be designed to increase ship speed ahead or astern by first increasing pitch. Further speed increases were to be accomplished by holding pitch constant and increasing power. It was also required that the propulsion system be controllable in either open loop power control or in closed loop speed control. Redundant manual control was required on the Propulsion Control Console and at a Local Operating Panel located in the machinery spaces. Manual control was to be independent of programmed control and was to operate using separate control of throttle and propeller pitch.

It was required that programmed control be designed to provide inherent protection against excessive propulsion system overloads and overspeed without reliance on existing protective devices. Tactical performance requirements were specified for crash stop and full ahead acceleration maneuvers.

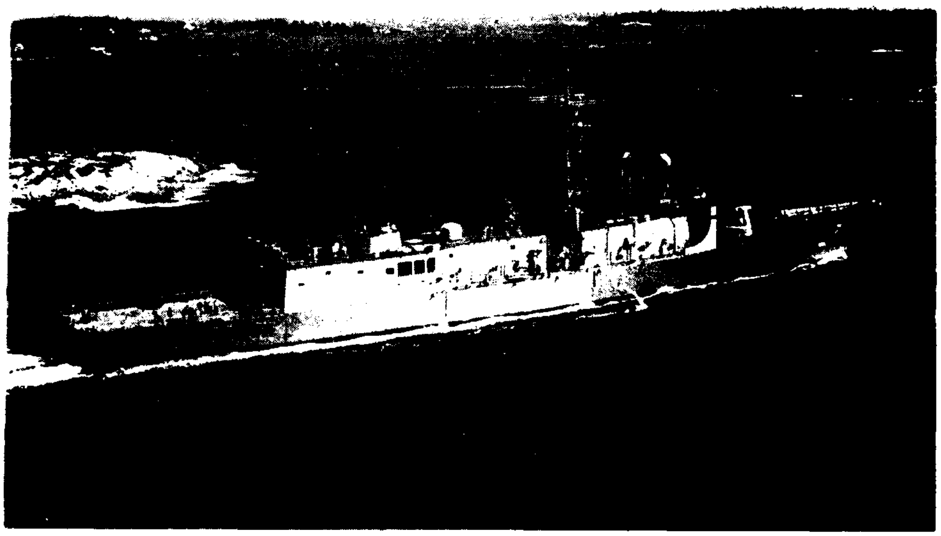


Figure 1 — FFG-7 on Sea Trials

MAIN PROPULSION SYSTEM

The prime movers are two General Electric LM2500 gas turbine engines. These engines are marinized versions of the aircraft derived CF6 jet engine fitted with free power turbine stages. Either or both engines drive through self-synchronizing clutches into a locked train double reduction gear. Propulsion power is absorbed by a 5 bladed, 16.5 foot diameter controllable-reversible pitch propeller. The engine output is controlled by throttle commands to its fuel control system. The engines respond to an analog power lever angle (PLA) command voltage to the engine's control module.

Propeller pitch is controlled by actuation of a pitch control solenoid valve on the propeller oil distribution box. Oil to the CP propeller hydraulic system is supplied by either one of two pumps. The main CP hydraulic pump is driven off the main reduction gear, so that oil flow and, therefore, pitch change rates are approximately proportional to shaft speed with this pump on line. The standby or independent CP pump is the same capacity as the main pump but is driven by a single speed motor providing nearly constant pitch change rates. Its capacity is sufficient to allow a full pitch change in either direction within a specified time. The attached pump is not intended for normal use during low speed or dockside maneuvering since pitch change rates at low shaft speeds are quite slow with this pump.

PROPULSION SYSTEM RATING CONDITIONS

Principal rating conditions specified for the main propulsion system are summarized as follows:

Maximum Rated Ahead Power	
Two Engine Operation	40,000 SHP
One Engine Operation	20,000 SHP
Maximum Rated Ahead Shaft Speed	
Two Engine Operation	180 RPM
One Engine Operation	146 RPM
Maximum Rated Astern Power	
Two Engine Operation	9,600 SHP
One Engine Operation	9,600 SHP

The design torque condition for the shafting and propeller is the two engine mode while the single engine mode is the design torque condition for the reduction gear. Twenty percent overtorques and overthrusts are specified for turning maneuvers. The astern power rating is based on steering gear limitations.

SIMULATION MODELS FOR DYNAMIC RESPONSE ANALYSIS (DRA)

Control system DRA uses simulation techniques to predict the response of the ship and main propulsion system to control inputs imposed by the operator under various control mode and environmental situations. The output of these simulations include time histories of ship speed, shaft speed, propeller thrust, propeller and engine torque, and numerous other parameters, as desired. In the case of the FFG-7 it was recognized that with the combinations of power and speed control with one and two engine operations using different types of pitch control in various types of maneuvers, and with controls transitions and gain investigations, the analysis would be extensive and require numerous simulation exercises.

The first detailed design DRA model available for FFG-7 applications was an adaptation of the General Electric SPADE 1 digital LM2500 ship propulsion dynamic simulation deck. This was modified to reflect propeller performance data, inertial constants, ship resistance data, and other system characteristics representative of the FFG-7 Class. An overall description of the model is given in the block diagram, Figure (2). The model assumes that propeller torque and thrust characteristics and propeller-hull interaction terms derived from steady state model testing are applicable to the dynamic case. Background on the dynamic theory and digital simulation approach can be found in References (1) and (2).

The SPADE 1 deck can represent either one engine operations or unisonous two engine operations, but cannot exercise the complex functions of programmed control involving mode transitions where the operations of two engines are not unisonous. It can, however, perform the simulations that are critical with regard to design for limiting of loads or to prediction of tactical performance in the crash ahead or crash stop maneuvers. Refined propeller data interpolation routines were incorporated in the SPADE 1 deck so that the deck simulations would have the benefit of smooth variations in propeller effects, to fit with the engine response modeling approach. Propeller cavitation effects were not included. Cavitation checks made at certain critical points confirmed that it would be reasonable not to include them, for the purpose and approach used in the DRA.

The SPADE 1 deck was used to generate extensive lists of high confidence steady state data. The data were used both to base steady state studies for formulation of control schedules and to base the simplified representation of engine response typically used in DRA. The SPADE 1 deck is a complex representation of gas turbine and ship propulsion dynamics. Because of its complexity and the simulations to be performed, the development of a simplified Exercise Model was essential. A simple engine response representation was used for the DRA Exercise Model capable of completely developing and exercising the programmed control routines for the FFG-7 application. Engine steady state data were organized into torque maps or data tables as follows:

$$Q_E = Q_E(N_G, N_{PT})_{T2}$$

Where: Q_E = Engine torque output

N_G = Gas generator speed

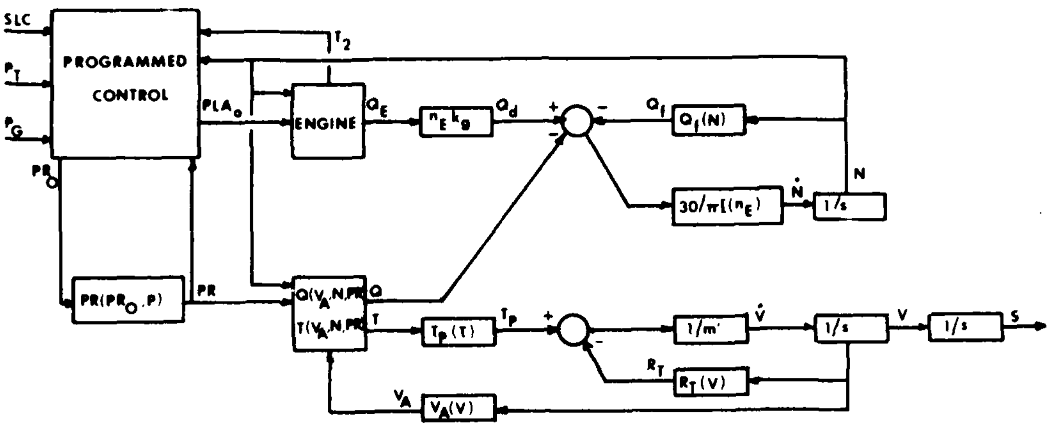
N_{PT} = Power turbine speed

T_2 = Gas generator inlet air temperature

The steady state relationship between the throttle input, PLA, and N_G was used, i.e., $N_G(PLA)_{SS}$ as an input from PLA to the engine torque maps. For dynamic representation the N_G output of this function was put through linear time lags before entering the torque maps. These lags are dominated by the inertial lag of the gas generator spindle for slow PLA excursions. The programmed control design required limiting PLA increase to a relatively low rate, for clutch protection, which supported the use of a fixed time constant for the Exercise model's purposes. The Exercise model otherwise included all of the Spade 1 methods for simulation of the ship response, including smooth (cubics) propeller map interpolations.

THE ANALYSIS AND DESIGN PROGRAM

The basic strategy of programmed control design for rapid extreme maneuvers was investigated in early studies using the SPADE 1 model. It was observed that high torque and thrust levels could



V_A Propeller speed of advance, ft/sec.

T_2 Compressor Inlet Air Temperature, °F

I Power train rotational inertia

k_g Gear reduction ratio, 20.0123

m' Ship mass including entrained water

N Shaft speed, rpm

n_E Number of engines clutched in

P P = 1. indicates that CP propeller hydraulic pump is motor driven. P=O indicates that pump is gear-driven

P_G Position of pot for manually adjusting gain constant used in speed control mode.

PLA_O Power lever angle ordered by programmed control

PR Propeller ratio as measured and fed back to programmed control

SLC Control lever position in terms of demand for ship speed in the steady state

PR_O Propeller pitch ratio ordered by programmed control

P_T Position of pot for manually adjusting time constant used in conditioning shaft speed error, in speed control mode

Q Propeller torque, ft-lb.

Q_d Engine torque developed on the shaft, lb-ft.

Q_E Engine torque output per engine, ft-lb.

Q_f Power train torque loss, lb-ft

R_T Total ship resistance, lb.

S Ship reach, ft.

s Laplace operator

T Gross thrust, lb.

T_p Net thrust, lb.

V Ship speed, ft/sec.

Figure 2- FFG-7 Dynamic Response Model

easily be developed without proper control thus making the demonstration of an adequate control strategy important. Before control strategies could be established computational programs were set up to produce required data lists on steady state relationships as follows:

(1) Ship speeds per shaft speeds at design ahead pitch.

(2) Ship speeds per shaft speeds at design astern pitch.

(3) Ship speeds and shaft speeds per pitches with minimum PLA, with one engine, per T_2.

(4) Same as (3), with two engines.

(5) Ship speeds per pitches for maximum shaft speeds found in (3).

(6) Ship speeds per pitches for maximum shaft speeds found in (4).

(7) Ship speeds per PLA at design ahead pitch, per T_2, for one engine.

(8) Same as (7), for two engines.

(9) Same as (7), for design astern pitch.

(10) Same as (8), for design astern pitch.

These data were assessed, partitioned, and synthesized using curve fitting methods as follows:

$PLA(V, n_E, T_2)$

$PR(V, n_E, m, T_2)$

$N(V, n_E, T_2)$

Where: V = ship speed

N = shaft speed

n_E = number of engines (1 or 2)

m = mode (power or speed)

T_2 = treated as continuous (to $1^{\circ}F$ resolution)

PR = pitch ratio

The data was confirmed using the Exercise model by generating steady state data per SLC position for the one and two engine cases, in speed and power modes, and over a range of T_2 values. These data formed the basis for programmed control schedules as discussed later. With this part of the design established, the Exercise model was used to make families of simulations for tuning the control strategy to handle worst case maneuvers requiring protection against overthrust and overtorque. The zero to full ahead maneuver was performed to develop required tactical performance, as was the crash stop maneuver with two engines. One by one, other features including parallel manual and programmed control and mode transitioning were exercised and developed into desired control configurations.

These simulation studies assumed full displacement, a clean hull, smooth water and average engine conditions. Further simulations considered the impact of increased ship resistance due to rough hull, wind and sea conditions, and of propeller load oscillations caused by wave action. The selection of speed mode feedback gains and speed limiting features were studied over a range of ship speed and wave effect combinations, using the SPADE 1 program. The control design developed limited the role of speed feedback to the maintenance of ordered average shaft speeds when the speed mode is applied, and to the compensation for propeller loading changes during pitch changes. This minimized the need for attention to problems of determining optimal gain and stability.

Further analytic effort included the translation of the FORTRAN version of the Exercise model programmed control subroutine into an integer arithmetic program to be implemented into the ship's operational system processor. At this point considerations of A/D and D/A interface scalings, precision of internal routines, tolerances to be applied for internal comparison tests as derived from sensor and line voltage variations, signal smoothing requirements, and some checks and redundancies for reliability purposes were incorporated. Means were added for handling variation of T_2 between the engines, and for calibration of PLA and pitch command signals to the design values used in the prediction model. The operational program was coded with design parameters expressed in forms that will expedite future changes or extensions of the control strategy, if necessary.

PRINCIPAL FEATURES OF PROGRAMMED CONTROL

A description of some of the key features of programmed control will be given here prior to presenting the results of simulations and trials. Additional description constituting a narrative type flow chart of programmed control is provided as Appendix (A).

Schedules

Ship speed as ordered by SLC position is used as the input demand signal to all of the schedules. The single lever input is calibrated in knots. Because the control design was based on specified ship displacement, hull, and calm sea conditions, achieved speeds will vary from demanded speeds according to variations of those conditions as well as through the limitations of the prediction-design process.

The requirement for open loop power control dictated that programmed control be designed so that steady state propeller thrust will be invariant with inlet air temperature at any given SLC position. The steady state analysis showed a strong influence of inlet air temperature on PLA required to produce a given level of engine output. This can be seen in Figure (3). Thus, the gas generator inlet air temperature sensor output signals are provided to the processor where they are used continuously in PLA schedule computations. Data from these computations are shown in Figure (4) for several values of T_2 for two engine applications. The PLA schedule output is limited to a maximum value corresponding to maximum rated power ahead or astern, i.e., $\overline{PLA} = \overline{PLA}$ (SLC, n_E, T_2) where SLC is equal or greater than that corresponding to maximum ahead or astern power. The PLA schedule for the single engine application is similar to Figure (4) except that the $\overline{PLA}$ is reached at a lower ahead speed demand. Also, $\overline{PLA}$ is higher for rated astern power since only one engine is available to achieve the same power.

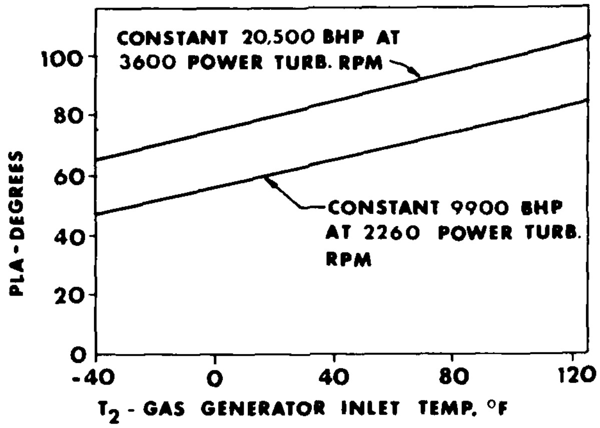


Figure 3 - Power lever angle
for constant engine output

It will be noted in Figure (4) that in the lower range of ahead and astern speeds PLA is scheduled at 13 degrees. This is the idling range where propeller pitch changes are scheduled. A PLA of 13 degrees corresponds to the minimum sustainable idle gas generator speed and is the condition of minimum engine output. The purpose of this schedule is to provide minimum propeller speed operations (in the power mode) to reduce hydrodynamic noise as much as possible. Operation at or near to design ahead pitch best satisfies this objective.

The speed control schedule for single engine operation is shown in Figure (5). Speed control in the idling range is scheduled so that a fixed shaft speed is maintained in the steady state for a given inlet temperature and number of engines applied. Minimum power is required at the point of minimum propeller torque load, and PLA is increased as required to maintain the same shaft speed as pitch increases. This design was adopted to meet the requirement that gas generator speeds be held as low as possible in the idling range. Higher shaft idling speeds occur with lower inlet air temperatures and with two engines operating.

Four pitch schedules were developed to support the power and speed modes, for one and two engine applications. The pitch schedule for two engine speed control operation is shown in Figure (6). Pitch and PLA schedules constitute multivariable function generators in the sense that the input T_2 is applied from -40 to 125 degrees Fahrenheit to one degree resolution.

Steady State Power Control

Operation at constant demand ship speed in the power control mode

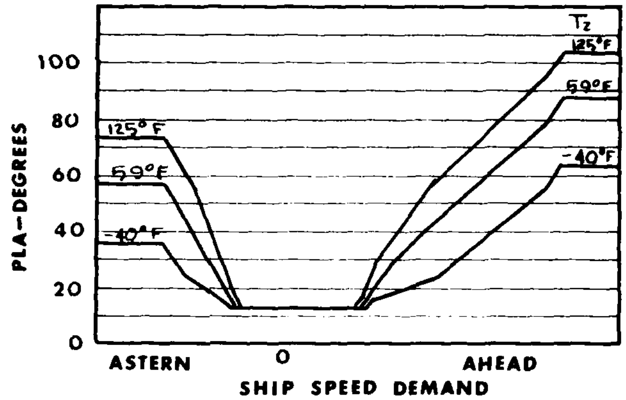


Figure 4 - Power Lever Angle Schedule, Two Eng. Mode

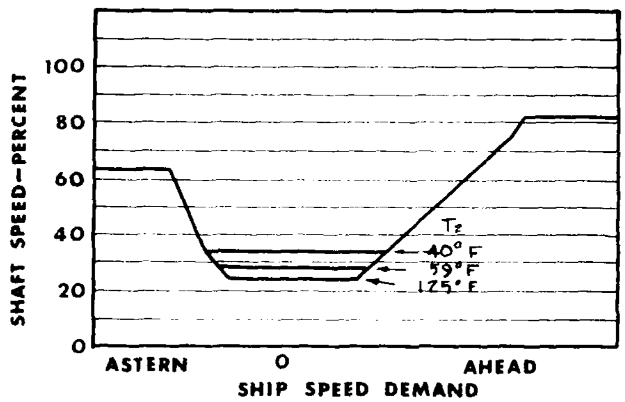


Figure 5 - Shaft Speed Schedule, Single Eng. Mode

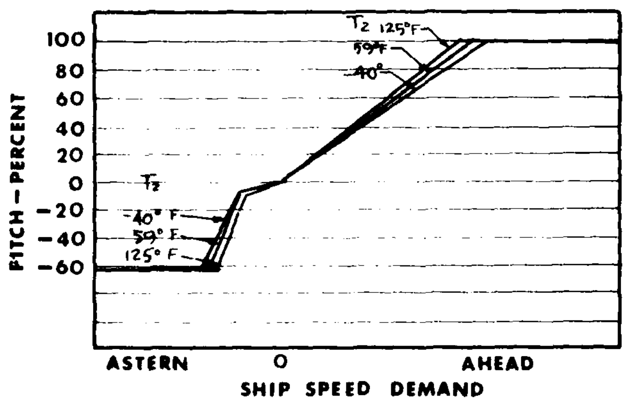


Figure 6 - Propeller Pitch Schedule, Two Eng. Mode, Speed Control

will be the common operating condition. The processor will command scheduled and calibrated PLA and pitch corresponding to the SLC position and T_2. In steady speed demand they will vary only in response to changes in T_2, which normally will be gradual, or in the case of operation in heavy weather, PLA will respond to the action of speed limiting functions when there are high speed demand and sea state combinations. Operation during turning maneuvers will be at very nearly constant power, and torque and thrust increases during turns will be moderate. This is favorable from the standpoint of propulsion system component stress levels. The controls were designed deliberately to be unresponsive during power control turns for this purpose.

Steady State Speed Control

In this mode shaft speed and pitch are commanded on the basis of speed mode schedules and pitch calibrations. PLA is commanded on the basis of the one or two engine schedules and calibrations. PLA is then augmented in response to shaft speed sensed error using proportional plus integral error conditioning. Gains for the proportional and integral terms can be varied independently by analog adjustments in the propulsion control console, although the gains established in simulations have been found quite satisfactory during actual operation up to this time. The gain signals are temperature compensated to sustain the similarity of dynamic response over the T_2 range. A switch is provided on the console to diminish gains for heavy weather operations.

Also, in speed control the magnitude of feedback augmentation is limited to diminishingly smaller amounts as power is increased by redefining and updating $\overline{PLA}$ as follows:

$$\overline{PLA} = PLA + K\ (\overline{PLA} - PLA)$$

Where: PLA is schedule output and K is a fraction less than unity.

This overshoot limitation is used to reduce the large increases in propulsion system loads during turning maneuvers which would otherwise occur in speed control if more freedom to counteract the tendency for shaft speed to drop during turns were allowed. Even so, loading during turns will generally be higher over the speed range than in power control and it appears advantageous from the standpoint of long term stress levels to use power control above the idling range. Speed control, however, is the recommended control mode in the idling range because it provides better ship responsiveness in low speed maneuvering situations.

Control of Acceleration Maneuvers

The control strategies for extreme ahead acceleration maneuvers were designed to meet two opposing requirements. It was required that programmed control be designed to prevent excessive overloads in the propulsion drive train, without reliance on an existing torque limiting device, by limiting the fuel ramp time. This provides protection in the event that normal torque limiting features are disabled or overridden. However, it is important to note that the engine response characteristics are rapid enough to cause high overthrusts even if torque is limited to no more than its maximum continuous value. The other requirement was that programmed control be designed so that the ship is capable of accelerating from dead-in-the-water to full power speed within a specified number of ship lengths. Consideration of these requirements and review of preliminary simulations led to the design goal that both overtorque and overthrust be limited by programmed control to approximately 120 percent of their maximum continuous values. This is considered to be a conservative limit for transient overloads. However, it was also recognized that simulation techniques were not fully proven and underestimation was a possibility. A complicating factor was that the tactical requirements were to be met using either the attached or independent CP hydraulic pumps. The slow pitch change rates at low shaft speeds with the attached pump on line had to be considered.

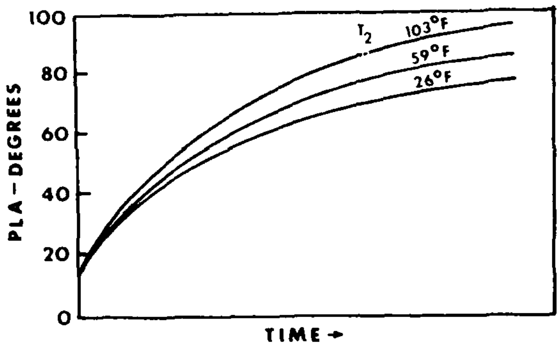


Figure 7 - Non-linear ahead acceleration rate limits

The solution developed was to limit PLA increase as illustrated in Figure (7). This type of nonlinear acceleration rate limit is effective in mitigating overloads since it delays the application of high power until ship speed has increased significantly. Increasing power more rapidly at lower speeds aids in increasing the rate of pitch change early in the maneuver when the attached CP hydraulic pump is used and serves the objective of rapid ship acceleration. The PLA rate limiting function is temperature compensated so that the performance during a full ahead acceleration will be independent of T_2. It is used in both the two engine and single engine modes. Rate limiting is required in the latter mode since the highest torque is imposed on the reduction gear during single engine accelerations.

Ahead accelerations over speed ranges above idling but less than full ahead are exempted from the nonlinear decreasing PLA rate limit in Figure (7). Instead, a fixed rate is used corresponding to that for the PLA at which the maneuver is initiated. This rate will be used as long as the shaft is accelerating at less than a set limit and PLA is less than $\overline{PLA}$. The rate will be reset each time that shaft acceleration is detected to be greater than the limit. This feature, exempting the full nonlinear PLA rate limit for less than extreme ahead accelerations, allows more rapid ship response under circumstances where overloads will not be encountered.

Outside of the idling speed range, all maneuvers involving changes in PLA commands are performed in the open loop using the appropriate rate limiting schemes. If such a maneuver is commanded while the system is in the speed mode, the speed loop is automatically opened, then closed when the scheduled PLA is achieved. After the loop is closed the feedback augmentation of PLA will provide temporary power overshoot and decrease the time required for the ship to steady out. The gains are conservative, however, and decreasing with higher scheduled PLA, supporting the protection against overthrust and overtorque in near extreme maneuvers.

Astern accelerations are limited using a simple linear rate of PLA increase. Maximum astern power is sufficiently low so that overloading is not a consideration. There are other design features that control accelerations which are primarily of use in the idling range. These are discussed separately.

Control of Reversal Maneuvers

Crash astern maneuvers are the most critical in this category. It was a requirement that programmed control be designed to stop the ship from maximum ahead speed within a specified number of ship lengths. In addition, it is during this maneuver that the highest astern thrust will be encountered. There is also potential for overspeed of the shaft caused by propeller feedback or windmilling torque, and under certain circumstances, for very low shaft speeds to occur due to increasing propeller loading when ship speed and pitch are in opposing senses.

The control strategy that evolved for this maneuver includes an immediate order to cut PLA to minimum at the maximum rate permitted by the engine controls as soon as the SLC lever has been moved astern past the position corresponding to zero speed. This helps to minimize the tendency for overspeeding when windmilling effects occur. It is also needed in emergency or low speed reversal maneuvers to minimize power application before the pitch has reversed sense. At the beginning of a deceleration maneuver calling for less than design ahead pitch, the pitch is held to design ahead until the shaft speed drops to a set level as a result of the power chop. This helps to limit windmilling and lowers a momentary peak in propeller blade spindle torque which was predicted to occur soon after the pitch change is started. A further measure is introduced to limit windmilling caused by pitch reduction at high ahead ship speeds. Since PLA is already chopped, the measure applied is to stop pitch change once it has started and if shaft speed has subsequently risen above a higher limit somewhat below rated speed. The pitch change resumes when the shaft speed drops below the limit. In FFG-7 crash astern maneuvers the engines declutch soon after the start of the maneuver and the anti-windmilling pitch freeze is held for several seconds.

In continuing the reversal maneuver, power is held at idle as pitch continues to move astern until it is near effective zero. PLA is then ordered to increase at its normal maximum linear rate to the scheduled astern level.

Reversals from astern to ahead are controlled in the way applied

ACKNOWLEDGMENTS

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differences between actual and indicated pitch, rudder action and weather conditions have all been ruled out as possible significant causes. It is hoped that later sea trials will shed more light on this matter.

Approximate measurements of head reach for the two crash astern maneuvers indicated somewhat better performance than predicted and that the tactical requirements would be met with ample margin. Reach measurements were not made for the zero to full ahead accelerations. However, other monitored parameters indicate the tactical reach requirements were conservatively met.

A single engine full ahead to slow astern maneuver was conducted with the motor driven CP pump: it being the most severe maneuver from the standpoint of the possibility of a shaft reversal. Shaft speed dropped to a low level causing pitch rate to slow and then to hold in accordance with design. The pitch controls responded rapidly to these respective commands and shaft reversal was prevented.

It is considered that the full scale trial results demonstrated successful achievement of propulsion control design objectives. Actual operating time on the FFG-7 is limited at the time of this writing. Most experience to date has been obtained during three sea trials totaling about nine days with a shipyard operating crew. However, the ship left the shipyard on its first trial in programmed control and operated almost entirely in this mode throughout the remainder of the trials. The trials included several hours of operation in rough seas during which time the propulsion system and its controls functioned normally. Programmed control maneuvers were observed to be smooth and operators commented particularly on the ease and effectiveness of control during crash reversal maneuvers.

CONCLUSIONS

1. The FFG-7 application of in-line digital processing for propulsion control provided great flexibility in the solution of control problems. The experimental firmware program, as an integral part of the dynamic analysis simulation program, was easily modified to represent alternative design solutions and was readily augmented to cover various maneuvering problems as they arose.

2. The digital control design facilitated the incorporation of automatic control modes, mode transitions and complex function generators. The design objectives to achieve consistent open loop control and to limit propulsion system overloads to conservative levels were met successfully.

3. The simulation model used for dynamic analysis, which neglected non-linear engine response, non-steady propeller and hull interaction effects and propeller cavitation, was adequate for the design approach. Agreement between simulation and full scale results was generally quite good.

4. The propulsion controls performed successfully throughout sea trials. This contributed greatly to the timely completion of the prototype program. Overall performance objectives were achieved and tactical performance well exceeded the requirements.

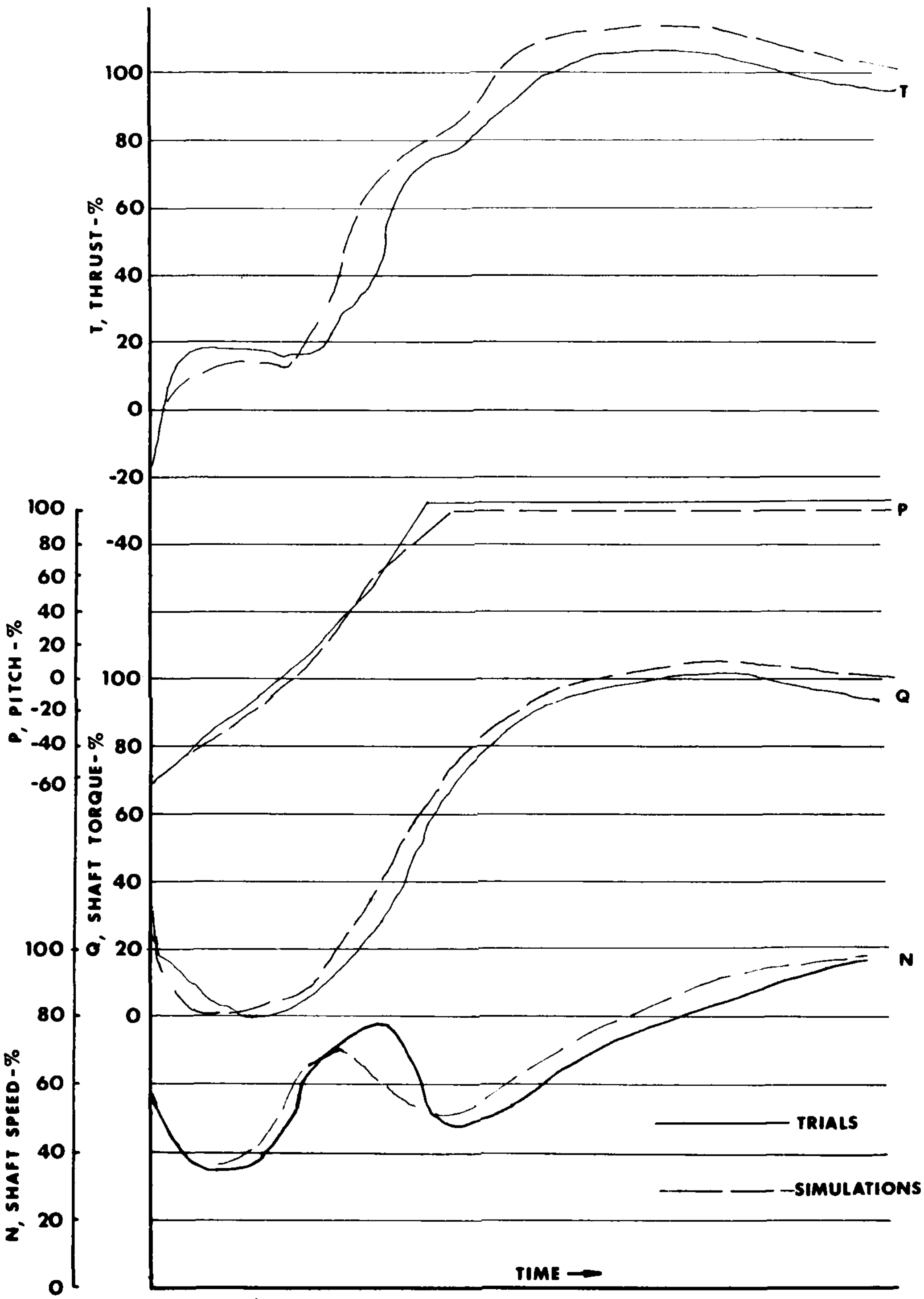

Figure 15 - Full Astern to Full Ahead,
Two Engines, Attached CRP Pump

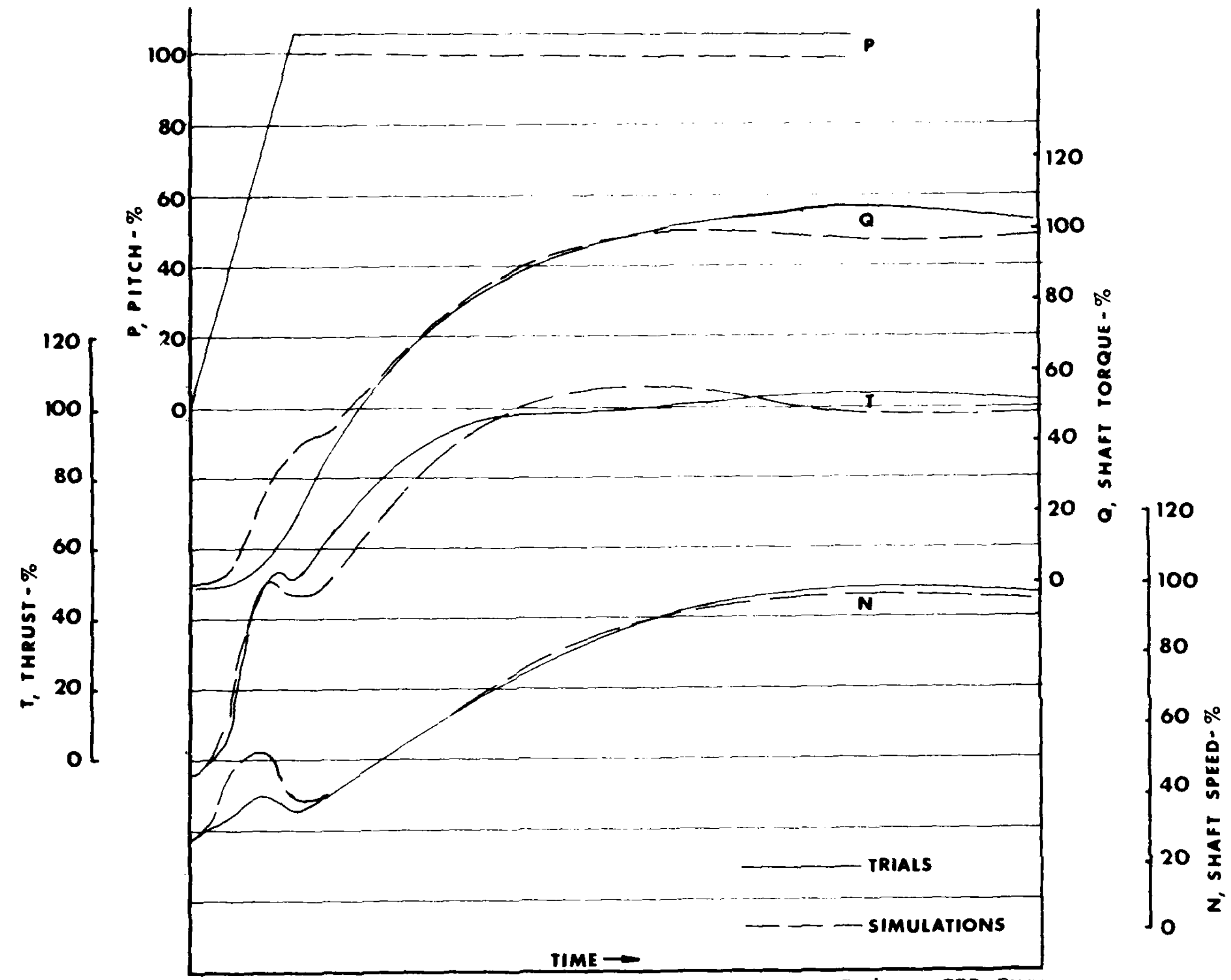

Figure 14 - Zero to Full Ahead, Two Engines, Motor Driven CRP Pump

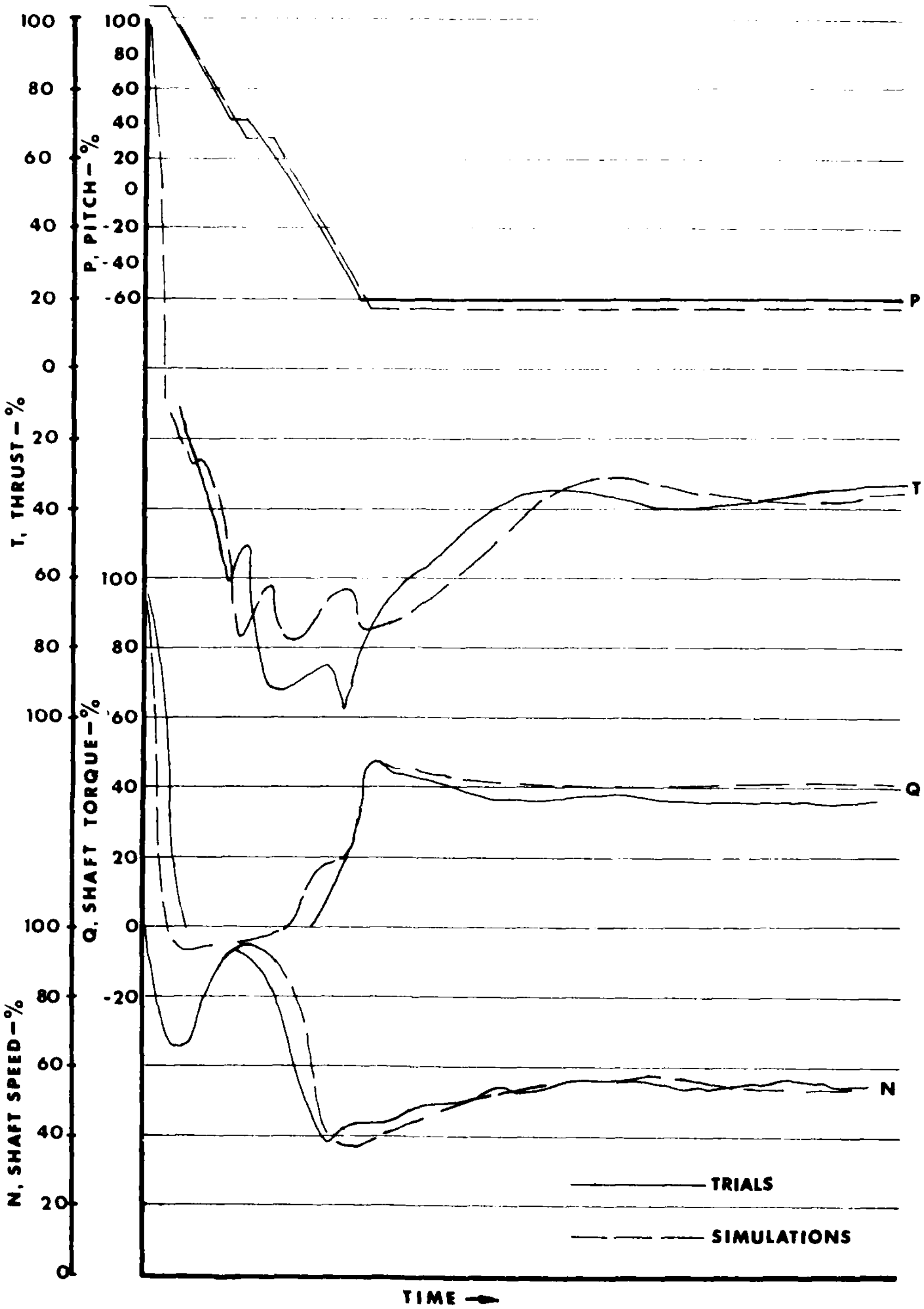

Figure 13 - Full Ahead to Full Astern, Two Engines, Motor Driven CRP Pump

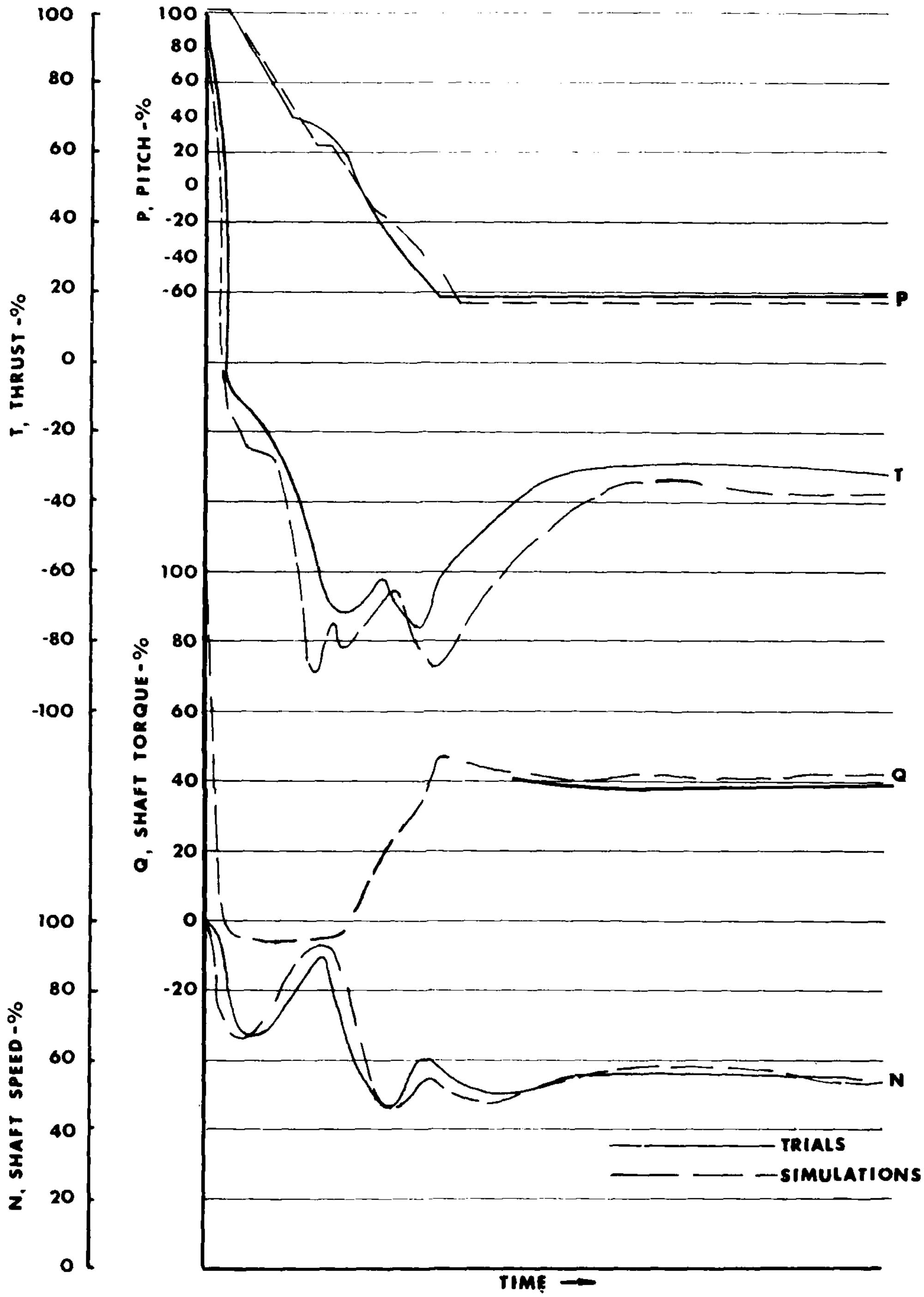

Figure 12 - Full Ahead to Full Astern,
Two Engines, Attached CRP Pump

PLA is immediately chopped to idle since, in the simulation, SLC has been rapidly moved from ahead past zero to an astern position. PLA is held at idle until forced speed is triggered when pitch has moved past a point near zero pitch. PLA is caused to increase since shaft speed is lower than the two engine reference idle speed (for $T_2 = -40^oF$). PLA rise is ended with pitch having reached its ordered value, thus terminating forced speed. PLA dips briefly in open loop to its scheduled value causing normal speed control to resume. Feedback augmentation increases PLA and shaft speed steadies out to the scheduled idle speed for $T_2 = 59^oF$. The control mode shown, i.e., two engines, speed control with the motor driven CP pump, is recommended for good ship responsiveness in low speed maneuvering situations.

An engine transfer from two to one engine in programmed control is illustrated in Figure (11). Parallel automatic and manual control comes into effect the instant Engine 1B has been switched to manual control. Engine 1B is brought down manually to idle and the speed control feature of parallel control causes Engine 1A to respond with feedback augmentation to maintain shaft speed.

SIMULATIONS VERSUS FULL SCALE

Sea trials of the FFG-7 were conducted off the coast of Maine during the Fall of 1977. The ship was instrumented to measure key parameters including shaft torque, thrust, shaft speed, indicated pitch, gas generator speed, and power turbine inlet temperature. Oscillographic recordings of these data were available continuously and monitored during the trials to assure safety of operations. Gradual power build-ups ahead and astern were used to verify steady state performance before major maneuvers were undertaken. The trial agenda were also planned so that several less than extreme crash ahead and astern maneuvers would be conducted well in advance of the time scheduled for extreme maneuvers. This provided time for onboard comparison of full scale results with simulations prepared specifically in advance for this purpose. Agreements were satisfactory and trials proceeded on schedule.

Comparisons are shown in Figures (12) to (15) for crash ahead acceleration and crash reversal maneuvers. Agreements are good, although some discrepancies do exist. Some of these can be attributed to inaccuracies in recorded data and to slight gas turbine set up and operating variations. Also, the relatively large differences between simulated and recorded design ahead pitch shown in Figures (14) and (15) were found to be the result of a pitch indicator calibration inaccuracy. After recalibration, the recorded pitch was approximately 2% higher than the design ahead pitch assumed in simulations.

The largest discrepancies appear to occur during the two crash astern maneuvers performed with different CP hydraulic pumps, Figures (12) and (15). In these maneuvers, the full scale measured peak astern thrust is higher for the maneuver with the motor driven pump than with the attached pump. Unfortunately, measured shaft torque was found to be greatly in error in the early part of the maneuver with the attached pump and is not shown. Also, negative shaft torque was not recorded. It is doubted, however, that differences in shaft torque are an explanation since both measured shaft speed and indicated pitch for the two maneuvers compare quite closely when thrust measurement differences are greatest. Differences in ship speed,

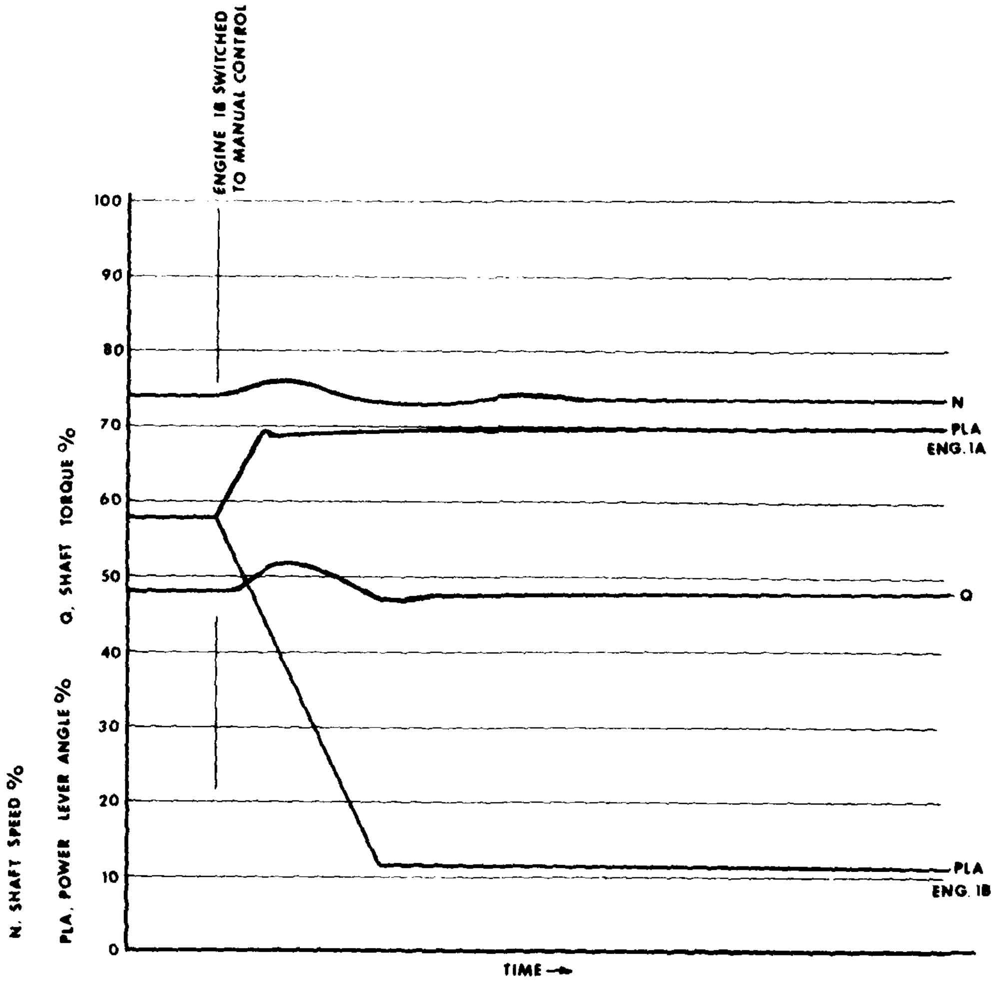

Figure 11 - Transition Simulation, Two to One Engine, $T_2 = 59^{\circ}F$

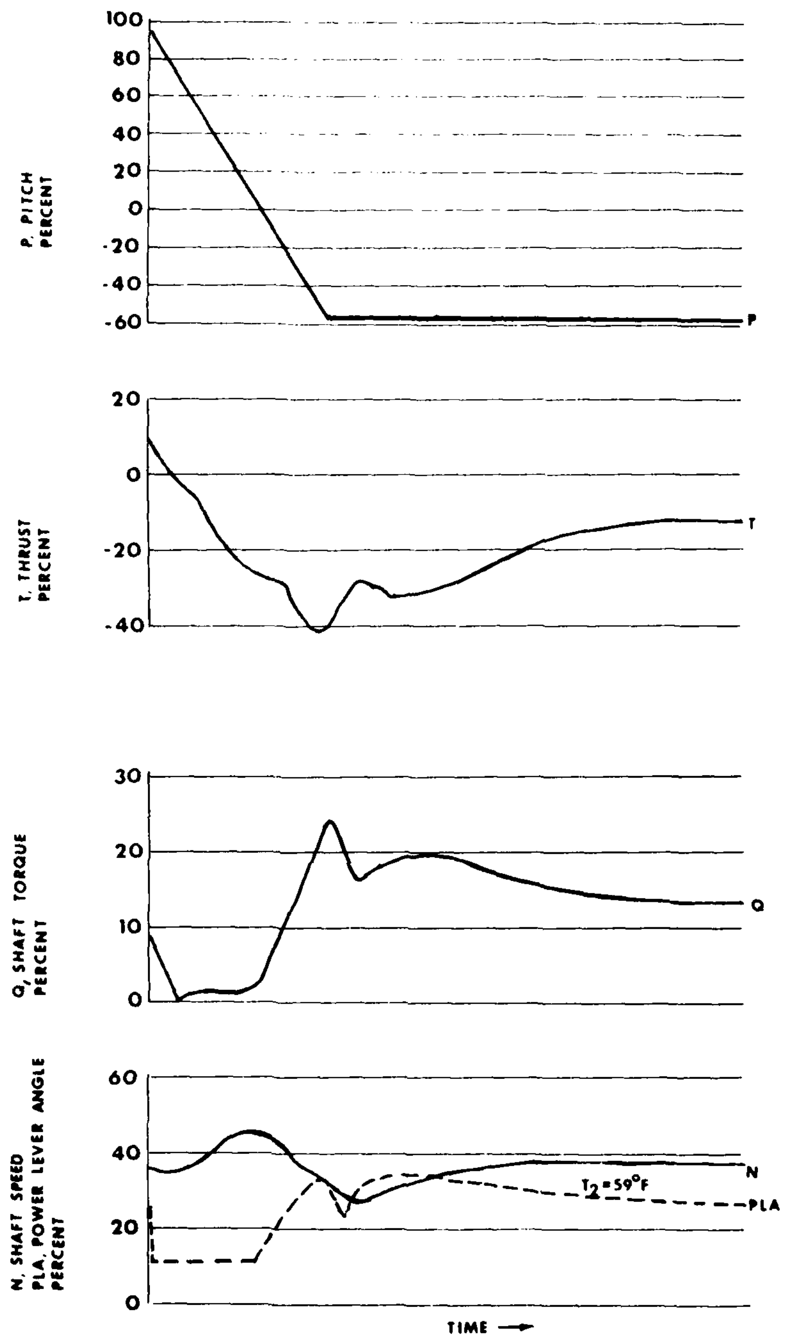

Figure 10 - Quick Reversal Ahead to Astern, Idling Range, Two Engines, Speed Control Mode, Motor Driven CRP Pump

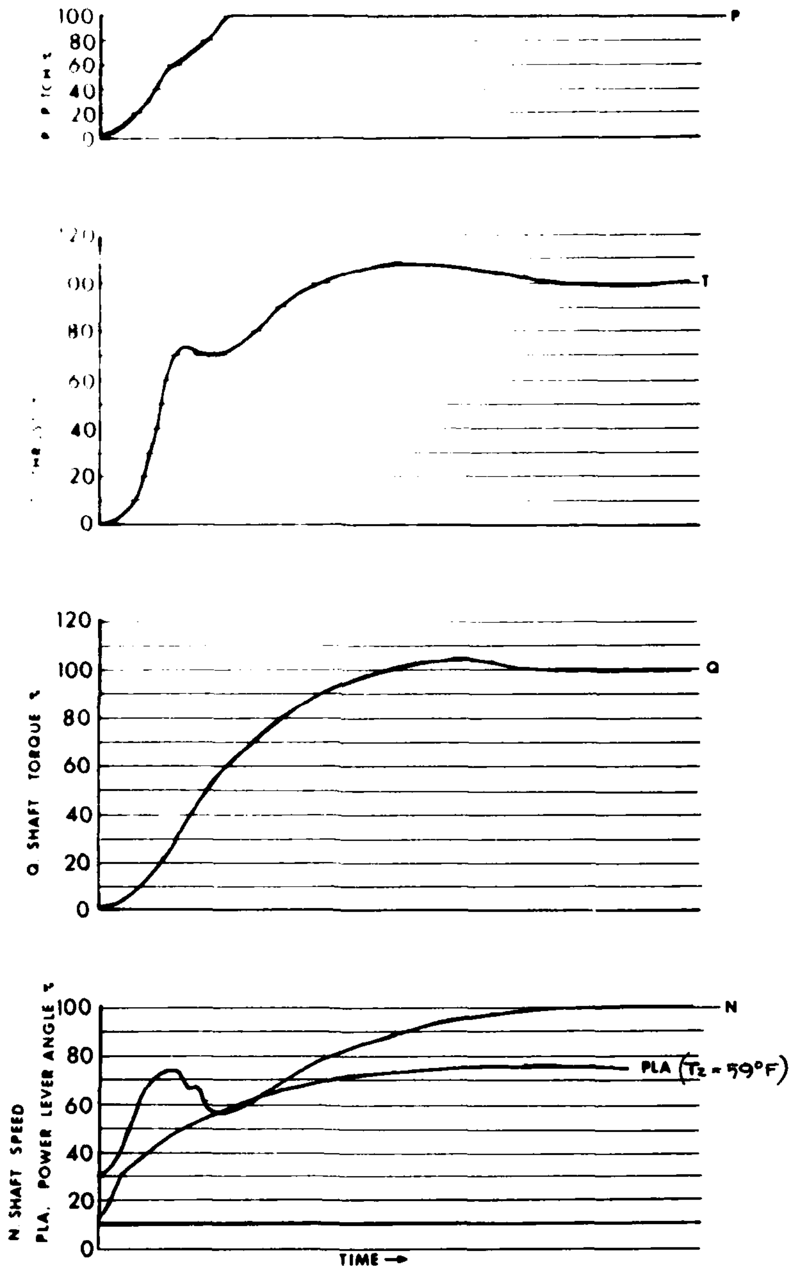

Figure 9 - Zero to Full Ahead Simulation, Two Engines, Attached CRP Pump

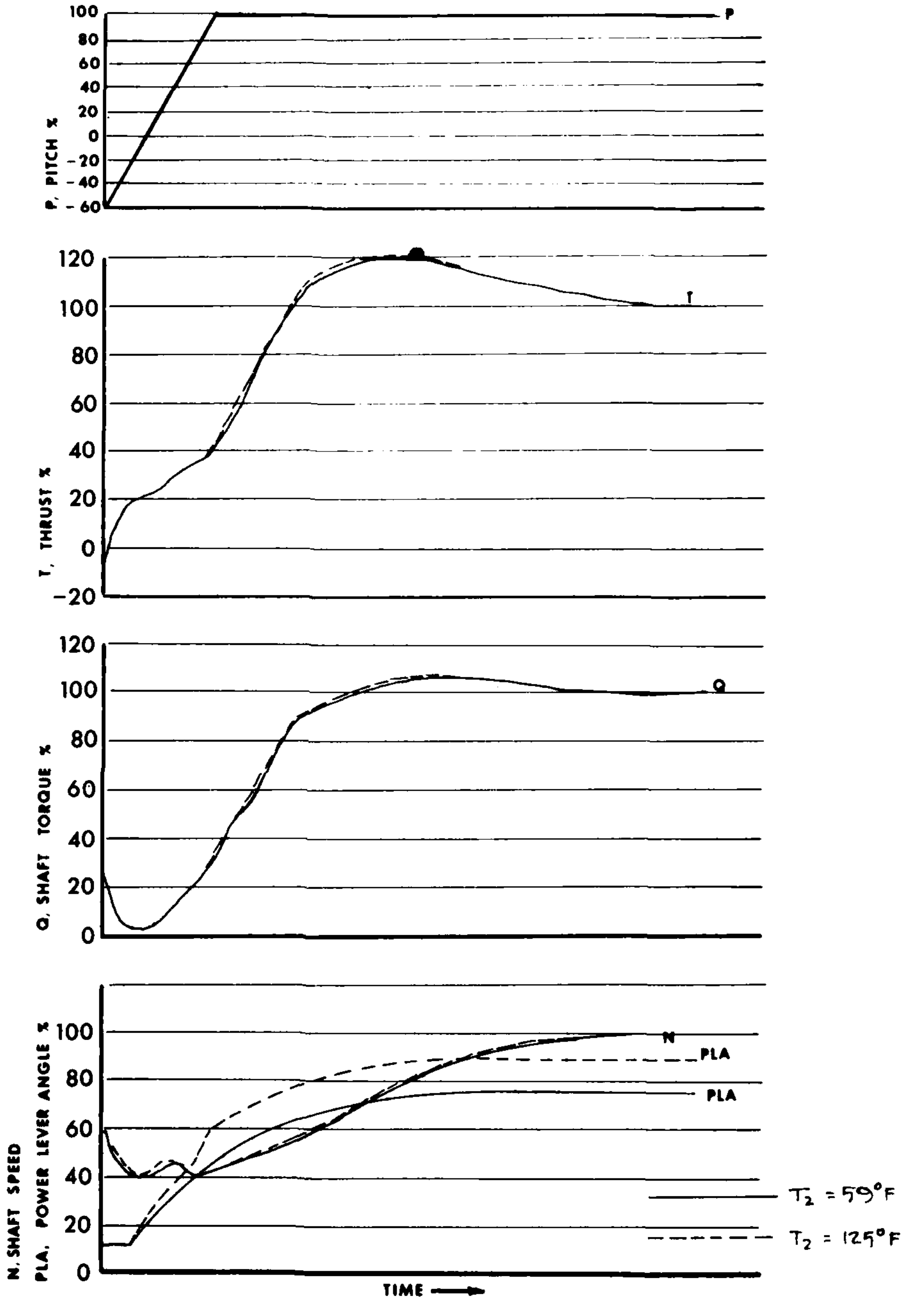

Figure 8 - Full Astern to Full Ahead Simulation, Two Engines, Motor Driven CRP Pump

clutch engagement limitations. The strategy is selected on a per cycle basis in the processor, so that the SLC can be moved during such transitions with smooth power train response.

If the processor detects that both PLA's must be lowered or both must be raised to achieve a newly scheduled two engine level, the PLA nearest to the scheduled level is held fixed while the other PLA is changed to its level. If this involves a decrease of the more remote PLA, the drop is made at a linear rate, but if it involves an increase the procedures for assuring against overthrust and overtorque are used. When the two PLA's are matched, they are similarly controlled to bring them to the scheduled value. In this case the logic applied is the same as is used for power transitions in response to an advance of the SLC in two engine programmed control, i.e., a general purpose routine handles all of the power transition situations.

Power Bias and Pitch Trim

The PLA schedules are based on average engine performance. Separate bias adjustments are provided for each engine on the Propulsion Control Console to permit calibration of the PLA command to the model used for the development of the schedules. Calibration of each engine to the same standard provides load balancing. The bias is read by the processor and PLA in excess of idle as computed from the schedules is adjusted using a multiplier which brings the maximum scheduled PLA or $\overline{PLA}$ to the demand required to achieve full ahead power of the engine applied. Engine calibration is most effectively applied by biasing each engine separately with maximum single engine power demanded. It can be accomplished, however, by tuning to achieve scheduled shaft speed at lower powers, in the power mode. Shaft horsepower readout is available based on torsionmeter signals for tuning to rated power.

Ahead and astern pitch can be trimmed by adjustment. Ahead and astern biases are applied with full bias applied to the pitch schedules at design ahead and design astern and reduced linearly so that no bias is applied at effective zero pitch. An additional trim is available to adjust pitch schedules so that effective zero thrust at zero speed can be tuned to the zero position of the SLC. This feature is included since an indicated zero pitch may not produce zero thrust. The bias is applied fully at zero speed demand and reduced linearly to the ahead and to the astern so that the bias is zero at design pitch levels.

SIMULATION RESULTS

The results of several simulations performed using the Exercise Model are illustrated in Figures (8) through (11). Simulation of an extreme maneuver from full astern to full ahead, Figure (8), was performed to demonstrate the effectiveness of programmed control in limiting overtorque and overthrust in this severe maneuvering condition. The consistency of results obtained for two widely different inlet air temperatures is noted.

The simulation shown in Figure (9) was conducted to demonstrate compliance with tactical requirements to accelerate from zero to maximum speed within a specified distance. Although not shown, the results indicate the requirement will be achieved with substantial margin.

Figure (10) illustrates a reversal maneuver in the idling range.

(3) A speed change is ordered requiring a thrust reversal: Here power will be cut to minimum level when it is sensed that a change of ship direction is ordered, and held there until pitch has approached effective zero. Forced speed then takes over until pitch reaches the position called for by the SLC position, after which control is returned to the original power or speed mode.

In all cases pitch will change at a rate depending on which CP pump is on line or on how slowly the SLC is moved. The independent motor driven CP pump will be used under low speed maneuvering conditions for better response. If this pump is not available, forced speed and temporary advance of the SLC can expedite the pitch change via the attached pump. The controls for low speed maneuvers operate in the initial portion of low to high speed maneuvers, e.g., forced speed operates to counter torque loading caused by pitch increases in the initial portion of a crash ahead maneuver. It also makes a significant contribution in maneuvers from very slow speeds to speeds slightly above idling.

Parallel Automatic and Manual Control

A special control mode is used to maintain control according to SLC demand when one engine is in programmed control and the other is in manual control. This mode will normally be used when one engine is brought off line and the other remains in programmed control. (Shutting down one engine must be done in manual control if the other engine is in programmed control.) Parallel control uses speed feedback with a simplified two engine shaft speed schedule and is automatically switched on or off according to engine control status. Normal engine shutdown requires a five minute cooldown with the engine at minimum throttle. Parallel control allows continuation of maneuvers via the SLC during this period. It uses shaft acceleration rate limiting to provide overtorque protection. The engine in programmed control is limited to the single engine $\overline{PLA}$.

Engine Transfers

Transfers involving removal of one of two engines from programmed control are accomplished by matching the manual control throttle setting to the existing throttle command displayed on the Propulsion Control Console. After the off-going engine is switched out of programmed control it can be brought to idle manually. The speed control feature of parallel control will provide smoothness of transfer when this is done.

Open loop transition routines are provided to handle operations in which an engine is brought on line to join a second engine already operating in programmed control. The oncoming engine is started manually and brought to idle, causing the engine in programmed control to be under parallel control. The oncoming engine can then be switched to programmed control, causing a discontinuity in the schedule output (a switch from a one to two engine schedule). In this case one PLA must be brought up from idling to the two engine scheduled level and the other PLA must be brought down from the one engine scheduled level to the two engine scheduled level. To do this the PLA that must undergo the largest change is ramped linearly at the maximum allowed rate and the other PLA is ramped linearly at a rate that will make arrival at the newly scheduled level for both engines simultaneous. The maximum allowable rate was based on self synchronizing for ahead to astern, with the exception that the final increase of PLA employs the contingent linear and nonlinear rate limiting already described.

During simulations of single engine reversal maneuvers with the motor driven CP hydraulic pump it was observed that as pitch went astern shaft speeds dropped to very low values, particularly in the case when a reversal from one engine full ahead to slow astern is ordered. This is because the engine response at low power is very limited as compared to the rate of loading on the propeller that is caused by astern pitch while the ship is still moving ahead at a substantial speed. In this situation the propeller advance ratio momentarily goes to high levels where there was some uncertainty in propeller data. Consideration of the above and the importance of insuring against shaft reversals prompted the incorporation of special measures to control this situation. Two shaft speeds, both lower than the idling levels were set. When the shaft speed drops below the first threshold, the pitch command is modulated to order change at half the rate otherwise available using the motor driven pump. When the shaft speed drops below the second threshold pitch change is stopped. Also, in response to dropping shaft speed, a "forced" or automatic speed loop used to counter propeller loading and a PLA boost triggered by the lower shaft speed threshold, will cause engine output to increase. These control features are discussed in the following sections.

Shaft Speed Limiting

When the shaft speed drops below the lower threshold of shaft speed a separate PLA augmentation or boost term is applied at a fixed rate. When the shaft speed exceeds the limit, the boost term is degraded at a lower rate. This boost technique is applied inversely when shaft speed exceeds an upper limit, above the maximum ahead steady shaft speed.

Strategies for Low Speed Maneuvers

Low speed or idling maneuvers involving pitch changes can be conveniently discussed in several categories:

(1) <u>A change in speed is ordered requiring a reduction in either ahead or astern thrust without change in thrust direction</u>: Here PLA is ramped down in open loop at a linear rate if the initial PLA is higher than the new scheduled value. If in the speed control mode, this mode will resume when the scheduled PLA is reached by the ramping procedure. Pitch will move to the newly commanded (lower) level according to the pitch schedule in effect.

(2) <u>A change in speed is ordered requiring an increase in ahead or astern thrust but without change in thrust direction</u>: This case involves control using <u>forced speed</u>. This term applies to the strategy that automatically closes the speed loop to counter propeller loading caused by an increase of pitch magnitude. Forced speed references maximum idling for the one or two engine case, i.e., the idling shaft speed for $T_2 = -40^{o}F$. Forced speed is discontinued when the pitch has reached its commanded position.

APPENDIX (A)

The flow chart shown in Figure (16) illustrates the approach of the programmed control procedure. The procedure is entered in each cycle of the propulsion control system processor, if only to monitor the control input status and to store information needed when programmed control is initiated. The following description is given.

Block No.

1 Entered every cycle of the PCS processor. Monitoring is done here to note which engine(s) is on line and which is in programmed control. PLA values for the engine(s) in manual control are recorded so that rate limiters used in transition from manual to programmed control can be initialized at current values.

3 Verifies if programmed control has been initialized.

4 Entered on the first cycle of programmed control. Sets terms to appropriate initial values, e.g., the integral term of shaft speed feedback is set to zero. A flag is also set to indicate initialization has taken place.

5 Determines control mode for schedule selection, i.e., one or two engines, speed or power control, normal or parallel control.

6 Generates propeller pitch schedule output. Two engine speed mode schedule is used for parallel automatic and manual control.

8 Generates PLA and shaft speed schedule output.

9 Computes limit on PLA command, $\overline{PLA}$, to limit propulsion system to rated output for one or two engines, ahead or astern.

10 Determines which, if any, pitch schedule command override is in effect.

12 Modulates pitch command if shaft speed falls below low limit.

13 Holds pitch if shaft speed falls below second lower limit. Also holds pitch in reversal from design ahead pitch until shaft speed falls below a set limit or holds pitch if shaft speed later exceeds second higher limit.

15 Generates parallel control PLA and shaft speed schedule outputs. The two engine shaft speed schedule is used in the idling range.

16 Selects those power command overrides dependent on ordered pitch changes.

18 Chops power to idle if pitch reversal is ordered. Speed control, if on, is turned off.

19 Speed control (forced speed) is turned on if pitch increase, ahead or astern, is ordered and shaft speed is below the

T_2 = -40°F idle speed reference value.

20 Determines type of transition ordered, if any. This includes change in number of engines in programmed control, change from power to speed control or vice versa, or change in single lever control position.

21 Applies non-linear or linear PLA rate limits for ahead acceleration. Applies linear PLA rate limit for astern acceleration. Applies linear PLA rate limit for non-reversing deceleration. Applies linear or non-linear rate limits required for one to two engine transitions. Speed control, if on, is turned off until transition is completed.

23 Scheduled PLA is incremented or decremented depending on shaft speed error conditioned terms when speed control is in effect. Proportional and integral term gains are reduced substantially with increasing scheduled PLA. PLA augmentation is limited to prevent excessive feedback during ship turns.

24 Boost terms decrease (or increase) PLA at a specified rate if shaft speed is higher (or lower) than upper (or lower) limits. Positive or negative boost terms are diminished at a lower rate when speed limits have been met.

25 PLA schedule, speed feedback and boost terms are combined but limited to $\overline{PLA}$ computed in Block 9, to minimum idle PLA and to the maximum allowable PLA increase rate.

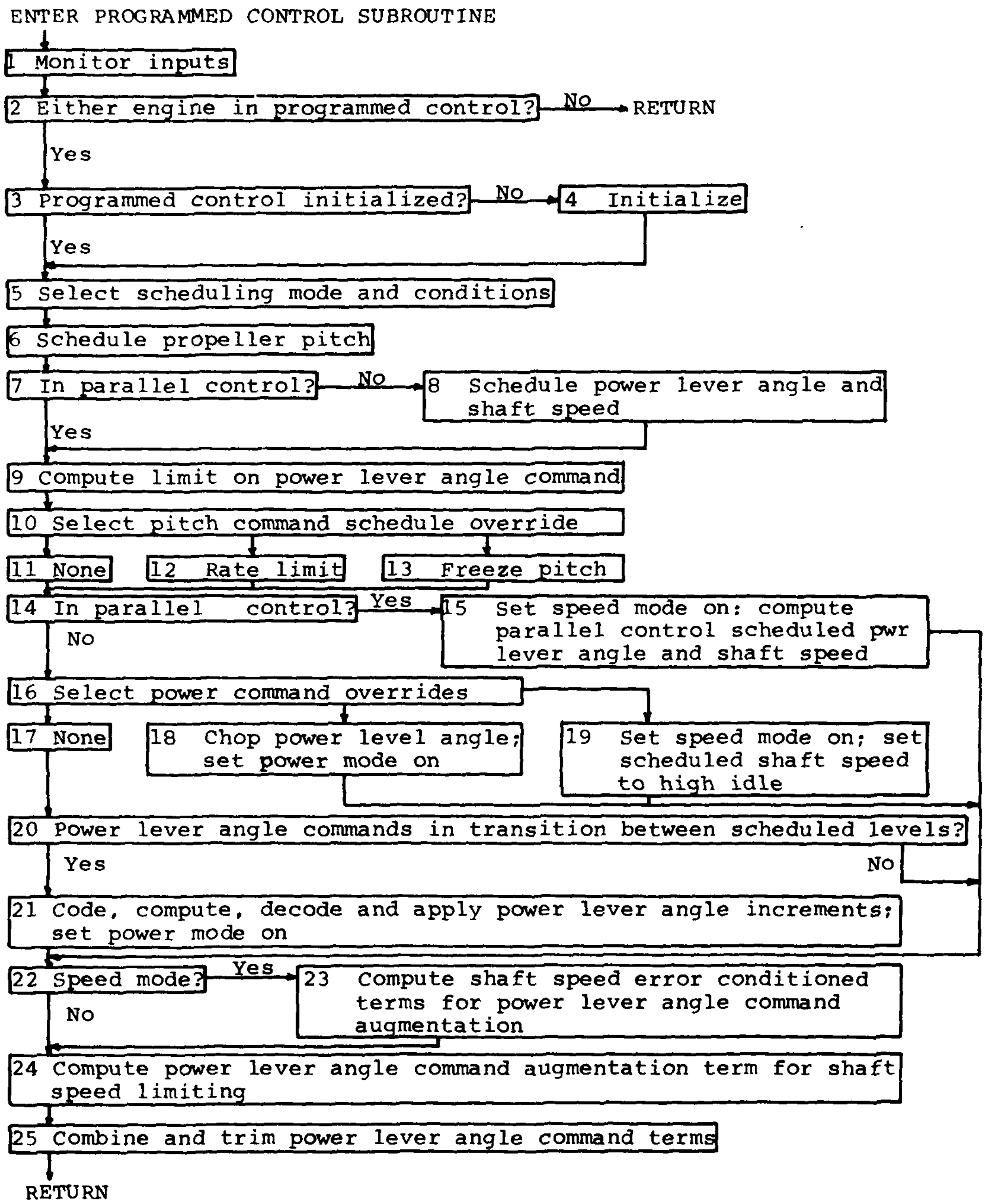

Figure 16-Programmed Control Subroutine

SIMULATION AND PERFORMANCE EVALUATION OF A MINE COUNTER MEASURES VESSEL CONCEPT

By: Professor R.V. Thompson, B.Sc., M.Eng., Ph.D., C.Eng., F.I.Mar.E., F.I.Mech.E.

ABSTRACT

Presented are the results of a combined mathematical analysis and simulation programme of the propulsion machinery and ship dynamics of a Mine Counter Measures Vessel Concept. Manoeuvres relating to both main and auxiliary propulsion modes are included and conclusions drawn regarding the optimum control configuration resulting from computed trials.

The concept evaluated consists of a single diesel per shaft, two shaft system driving through a reversing clutch and reduction gear box to two fixed propellers for the purposes of main propulsion and an hydraulic drive concept with jet reaction bow thrusters for the slow speed, search domain. The latter system involves a four pump concept for the distribution of power between hydraulic drive and thrusters.

Of particular interest are the transient loads generated on the propulsion machinery and associated clutches during crash back manoeuvres together with the effect of hydraulic system compliance on main shaft rotational stability.

INTRODUCTION

Indigenous to the role of Mine Counter Measures Vessel concept is the capacity to manoeuvre about a fixed station with the minimum of noise and drift. Furthermore, the vessel should demonstrate a capability to sweep at a constant speed together with the capacity to accelerate to maximum towing speed when streaming or heaving-in at maximum electrical load.

In order to achieve these objectives the concept indicated in Figure 1 was generated as the subject for analysis under simulated manoeuvres on an extensive Hybrid Computer facility at the University of Newcastle upon Tyne. As may be seen from the diagram the main propulsion mode consists of two medium speed diesel engine shaft sets with individual reduction gear boxes and fixed pitch propellers. Reverse drive is achieved by the activation of hydraulic clutch systems.

In order to achieve an infinitely variable speed profile in the forward/aft direction within the capacity of the propulsion system during the surveillance mode, a series of hydraulic swash plate/motor systems were designated - one complete set per shaft coupled to the main system via the gear boxes by pneumatic clutches. Lateral motion to be predominantly controlled by the use of a bow thrust system using the force generated by the rate of change of momentum resulting from pumping water via orificies situated in the bow section each side of the longitudinal axis of the ship.

Thrust modulation could be obtained by a combination of hydraulic rate and diverter valve control. The engine involved had to meet the added requirement of satisfying the somewhat eccentric demands of an electrical pulse generator. An integral gearbox hydraulic clutch system completes the assembly.

As a point of interest the hydraulic swash plate pumps are conceptually required to provide winching as well as propulsive power - a situation not evaluated in this study.

Basic Requirements

The overall objectives of the simulation programme were effectively as follows:-

To develop a simulation of the ship dynamics and propulsion machinery of the proposed MCMV which may be used to:-

a) evaluate the performance requirements and limitations that may be imposed on the various items of machinery during specified manoeuvres

b) establish and define, in the form of a detailed performance specification, the control system requirements associated with:-

   i) Main Engine Speed Control

   ii) Main Engine Hydraulic Clutch Sequencing

   iii) Auxiliary Diesel Speed Control

   iv) Hydrostatic Drive Speed Control

   v) Bow Thrust Control

that will provide the optimum compromise between response, stability, simplicity (and, hence, reliability) and maintainability.

The General Approach

A brief glance of the foregoing leads to the conclusion that the overall programme could be divided into two distinct phases, i.e.:-

1. Main Engine Propulsion Mode

2. Auxiliary Propulsion Mode

when evaluating overall vessel performance and the resulting data has been presented in these categories. However, in order to achieve a manageable approach to the problem of mathematically modelling a relatively complex vessel propulsion system as opposed to analysing its results, alternative sub divisions were generated, these being as follows:-

Phase 1 - Sub System Simulation Development. In this phase the total machinery content was divided into four sections each being evaluated separately. Group interaction was not evaluated at this stage. The sections selected are listed below:-

Section 1 - Main Engine Propulsion System
Comprising:

Main engine and governor
Reversing clutch
Reduction gearbox
Propeller and ship dynamics

Section 2 - Auxiliary Diesel
Comprising:

..... Comprising:

Auxiliary engine and governor
Reversing Clutch
Reduction gearbox
Pulse generator inertia

Section 3 - Hydrostatic Drive
Comprising:

Hydraulic pump and motor
Transmission lines
High and low line relief valves
Reduction gearbox
Propeller and ship dynamics

Section 4 - Bow Thrust System
Comprising:

Hydrostatic drive
Salt water pump
Salt water piping
Diverter valves
Eductor nozzles

Within Phase 1, a simulation of each of the four groups of machinery was developed and a preliminary evaluation of sub-system performance obtained. Prior to establishing each simulation, a linearised frequency response analysis was undertaken to obtain the dynamic characteristics of each group of machinery in terms of stability margins, natural frequencies and parameter sensitivity.

Phase 2 - Complete System Evaluation. By combining the sub-system simulations, where necessary, a fully interacting model of the main and auxiliary systems was obtained. Evaluation of alternative control system configurations was then completed for specific manoeuvres. Phase 2 effort was divided into three sections, defined as follows:-

Section 5 - Evaluation of Patrol, Cruise and Minesweeping Roles

Section 6 - Evaluation of Minehunting Role

Section 7 - Controls Systems Selection and Specification

In each role of operation, machinery limitations and control system performance characteristics were obtained. Simulation results were then reviewed and the final control system designs selected.

Details of the approach together with an analysis of the results obtained are continued in the following sections.

Section 1 - The Main Propulsion System

As the heading suggests this section was primarily concerned with evaluating ship and main propulsion machinery performance during ahead and astern manoeuvres in the Patrol, Cruise and Minesweeping roles.

Main propulsion was to be achieved by two diesel engines, driving through an hydraulic reversing clutch and reduction gearbox to two propellers. The clutch and gearbox to form part of an integrated engine package (see Fig. 2). Engine speed control was by a governor having a nominal design speed droop of 20% with clutch operation achieved by means of an engine mounted hydraulic control unit (H.C.U.).

With the H.C.U. a cam converted ahead/astern shaft speed demand from the set speed servo into equivalent governor set speed demands. The cam also operated a shuttle valve which controlled hydraulic pressure in both the ahead and astern clutches.

An engine driven fixed displacement pump provided hydraulic power to the H.C.U. and clutch. A relief valve across the pump limited maximum pressure.

Sequencing of set speed and clutch pressure was arranged to achieve the following:-

* Ahead clutch engages for ahead lever demands above engine idle

* Astern clutch engages for astern lever demands above engine idle

* With the lever in neutral, both clutches remain disengaged

An additional control feature provided within the engine package prohibited ahead clutch disengagement if fuel rack setting was less than a given value (usually close to idle rack setting) which was to be set by a micro switch mounted in the rack linkage. In operation, this feature prevents astern clutch selection at high forward ship speeds independently of speed demand lever position.

Linearised Analysis. Following normal analytical procedure the engine speed control loop was evaluated using linearisation techniques applied to a range of significant operating points. In all cases steady state engine data was used to determine the relationship between main engine developed torque and crankshaft speed. Relevant form of equations are shown in Appendix A.1.

Fig. 3 shows a simplified block diagram of the speed loop illustrating the interdependence of the various linearised components, load slope $\partial Q_L/\partial N_e$, assuming normal propeller design and operation, will always be positive and hence exert a stabilising influence on the loop. Minimum stability margins could, therefore, be analysed by its 'mathematical' elimination; an assumption which is valid for clutch disengaged operation and pessimistic for loaded condition.

Subsequent derivation and insertion of the relevant partials, data etc. lead to the frequency response characteristics indicated in Fig. 4 covering the situation of idle r.p.m., zero load and M.C.R., clutch engaged full propeller load. Fig. 5 shows the effect of governor time constant on relative stability.

This linearised frequency response analysis leads to the following preliminary conclusions affecting design:-

a) Stability margins are strongly dependent upon governor dynamics.

b) Bandwidth of the loop in the idle-declutched condition corresponds to 3 cps with an ideal governor setting, falling with increase in lag.

c) At rated power the corresponding bandwidth is approximately 1/3 cps and stable to the extent of being virtually independent of 'normal' spread of governor response.

Furthermore, it may be argued that as the inertia of propeller/shaft etc. referred to engine shaft is nominally less than 30% of declutched engine gearbox inertia, similar response may be anticipated in both cases when subjected to transient demands. Naturally, this only applies to the condition of the 'first overshoot' as hydraulic forces generated by propeller/water interaction have an increasing effect on load beyond this point - hydraulic slip taking place initially.

Hysteresis effects resulting from non linearities such as friction and/or backlash in the fuel rack linkage were also investigated using describing function techniques and are shown superimposed on Fig.4. The net anticipated effect of this hysteresis is to produce limit cycling in the speed regulation circuit at the idle/declutched condition at an amplitude and frequency indicated by the intersection point.

Fig. 6 indicates the theoretical relationship between 'hysteresis width' limit cycle amplitude and frequency versus variation in governor time constants, e.g. at $\tau = 0.1$ second, limit cycle frequency = ± 9 crpm at 1.25 cps for a 1 degree rack of hysteresis. Although the describing function technique is approximate, sufficient confidence may be attributed to the technique to suggest that speed oscillation can be contained within acceptable limits providing that hysteresis is limited to 5% of total rack displacement.

Simulation Technique. Following normal simulation procedure relating to symmetrical twin screw propulsion machinery systems only one shaft set was modelled with ship resistance characteristics being modified accordingly. Naturally, this technique raises the spectre of credibility regarding propeller interaction, lateral manoeuvre evaluation etc. However, at the time of analysis this data was not available and the inclusion of 'guesstimates' could prove detrimental rather than beneficial. Consequently, in line manoeuvres only and their effect on the propulsion machinery, associated controls etc. form the basis of the results presented.

Specific details of the pertinent modelling techniques are itemised below.

a) Diesel Simulation:

Simulation of the diesel engine was achieved by direct application of the equations given in Appendix A.1 so that simulated diesel performance would be accurate over the full speed and load range. A time constant of 0.1 seconds was assumed initially to represent governor dynamics. The following non-linearities associated with the actual hardware were also included in the engine model:-

i) variable fuel rack limit as a function of engine speed

ii) the maximum amount of power which the engine could absorb was limited to the 'hot' motoring power

iii) inertia referred to the crankshaft was set to change with clutch state.

Fig. 7 shows the computer patch diagram for the diesel simulation.

The dynamic performance of the engine model was found to be in close agreement with that predicted by dynamic analysis as too was the comparison between steady state performance and supplied data.

b) Reversing Clutch Simulation:

The schematic diagram of Fig. 8 shows how the clutch simulation interacts with the engine control system and propeller shaft variables.

Two logic input signals are applied to the clutch simulation:-

i) clutch engage or disengage selected

ii) ahead or astern rotation selected

These signals are supplied by the control system and H.C.U. in the complete system model. The simulation uses the above logic signals, together with engine and shaft speeds, to define clutch state as either 'locked' or 'not locked'.

When disengage is selected

1. clutch goes to 'not locked'

2. engine load torque goes to zero

3. inertia seen by engine changes from total clutched inertia to the declutched inertia

4. shaft speed is determined by propeller and friction torques acting on the free shaft and propeller inertias.

When engage is selected

1. slipping clutch torque is applied to the free propeller shaft in the correct sense 0.8 seconds after selection

2. a torque equal to the slipping clutch torque is applied to the engine 0.8 seconds after selection

3. engine inertia remains at the de-clutched value (J_{de}) whilst the clutch remains in the 'slipping' state

Clutch state goes to the 'locked' condition when shaft speed reaches equivalent engine speed. At the same time:-

1. engine inertia changes to full clutched inertia (J_d)

2. engine load torque changes to propeller torque + friction

3. shaft speed is constrained to follow engine speed

Ahead/astern select logic is necessary to ensure that:-

1. engine sees correct sign of propeller shaft load

2. propeller shaft sees correct sign of clutch torque when clutch is slipping

3. clutch sees correct sign of engine speed

Clutch slipping torque was set up as a function of engine speed. Fig. 9 shows how the simulation compares with the actual hardware. It can be seen that correlation is excellent over the engine speed range of interest. Fig. 10 shows the patch diagram for the reversing clutch.

c) Simulation of H.C.U. and Engine Control Systems

The hydraulic control unit within the engine package performs a number of control functions of direct interest to the evaluation of engine speed and clutch sequential control.

Fig.11 shows how simulation of the set speed servo and H.C.U. was achieved and how clutch operation and governor set speed variations were introduced.

The set speed servo was represented by a rate limited actuator whose maximum rate could be readily adjusted for the purpose of control system evaluation. The integrator within the servo loop was controlled by clutch pressure logic, thus representing the hydraulic detents in the cambox.

For simplicity, ahead and astern lever demands were derived from two separate signal sources which could be varied individually between idle and maximum set speed.

When set speed was increased above idle, an 'engage select' logic signal was transferred to the clutch simulation. A constant time delay of 0.8 seconds was then imposed before:-

i) clutch slipping torque was applied to the propeller shaft

and

ii) the cambox detent was released and set speed allowed to increase to the value demanded by the lever

To simulate the microswitch and solenoid arrangement which, in practice, prevents the ahead clutch from disengaging if the fuel rack is below idle, a comparator was set to switch when fuel rack setting was above a pre-set (but adjustable) value. The computer output logic signal was then fed into an AND gate together with the clutch engage/disengage signal. The output of the AND gate was then transferred to the clutch model as the clutch select signal.

Using set speed rate control in conjunction with the H.C.U. control options described, the following control system configurations may be evaluated:-

i) ship and machinery performance -v- various rates of application of governor set speed

ii) adequacy of 'open loop' clutch sequential control

iii) engine speed and clutch control examination with and without the 'Astern clutch protection scheme' associated with the solenoid inhibiting ahead clutch disengagement during high forward ship speeds.

Each of the above control schemes may be classed as 'open loop' or 'scheduled control offering the hypothetical, advantages of simplicity, low cost, high reliability and minimisation of stability problems.

The main disadvantages of the 'scheduled' control system schemes are:-

* Demanded speed is not met due to governor droop
* Clutch engagement is uncontrolled and could result in excessive power loss during severe manoeuvres
* Clutch protection schemes, if employed, can result in excessive penalisation of ship performance

More sophisticated control system alternatives worthy of investigation could be:-

i) isochronous control of propeller shaft speed to eliminate the effect of governor droop

ii) more accurate detection of clutch state (H.C.U. detects clutch hydraulic pressure) by comparing clutch input and output speeds. By this technique the transition between 'slipping' and 'locked' states can be detected accurately.

Application of the least complex control schemes to the propulsion machinery system were investigated initially in the hope that should performance prove to be satisfactory the need for additional complication, although academically stimulating would, from the point of view of programme completion, prove to be unnecessary.

d) Simulation of Propeller and Ship Dynamics

All relevant propeller data was replotted in the form of K_T^1, K_Q^1 -v- J^1 for ahead and astern shaft rotation. Figs.13 and14 indicating the measure of agreement obtained between supplied data and computer model.

The thrust developed by one propeller was compared with 'half ship' resistance and excess thrust applied as an acceleration or deceleration force acting upon half of the effective ship inertia.

Equations used in the simulation are shown in Appendix A.1.

Ship resistance was generated as a function of ship speed as indicated in Fig. 15. Control system evaluation was undertaken on the basis of 'deep hull' conditions with further overall assessments obtained at the clean hull and maximum towing resistance conditions. Propeller shaft friction was assumed to consist of two discrete components considered to be additive and always acting in opposition to shaft motion, producing resistance forces proportional to shaft speed and propeller thrust respectively.

Stiction was estimated at some 5% of clutch slipping torque at engine idle and therefore neglected. Fig.16 shows the computer patch diagram used in the simulation.

Section 2 - Auxiliary Propulsion Mode

An engine having similar characteristics to those identified in the Main Propulsion Mode was considered applicable to the slow speed manoeuvring requirements although with a reduced governor droop of 6%. The engine was assumed to be directly connected to an electrical pulse generator together with an integral gearbox via an hydraulic clutch assembly. The gearbox output member was designed to drive four pumps of the positive displacement type in either of two modes - ie propulsion or winching, the latter being ignored in this study.

Considering the propulsion mode only, each propeller could be driven by a hydraulic motor via a pneumatically operated clutch, each motor being supplied by its own individual pump. The two remaining pumps were to operate in tandem on a motor directly coupled to a centrifugal seawater pump designed to supply the bow thrust system.

In order to minimise cavitation in the hydraulic transmission lines a boost system was employed to maintain a sensible minimum pressure with differential line pressures being limited by suitably placed and set relief valves.

The centrifugal pump was designed to supply sea water to primary thrust nozzles via diverter valves. Pneumatic clutch engagement/disengagement could be initiated by means of a solenoid operated selector valve which either vented or pressurised the clutch upon demand. Interface between hardware and control system was via pump actuator.

System Development.

a) Auxiliary Diesel Engine

Equations similar to those developed for the Main Engine Simulation were used with suitable modification to the overall constraints (See Appendix A.1) and require little amplification.

b) Slow Speed Drive

To all intents and purposes the slow speed drive system relates to a conventional flow controlled hydraulic drive assembly and in consequence could be analysed using the appropriate 'text book' equations together with miriad assumptions. Some degree of complication resulted due to the need to cater for the discontinuity caused by the various clutching situations viz; locked, disengaged and slipping.

The effect of hydraulic line compliance on system response and stability superimposed an additional degree of complexity together with a substantial gain in interest!

Specific forms of the equations used in the simulation are shown in Appendix A.1 Section 3.

c) Bow Thrust System

The hydrostatic drive model involved to satisfy the requirements of lateral thrust generation was similar to that of the slow speed system with constraints or variations.

The two hydraulic pumps acting in tandem were represented by a single unit having twice the displacement gain and leakage coefficients of each pump. Transmission line differences were incorporated as too were motor and load inertia variations.

The overall model was further simplified by ignoring low pressure line dynamics, relief valve and boost system performance - a ligitimate undertaking due to the unidirectional operation of the system. Equations used are included in Appendix A.1.

The equations representing the thruster nozzles were developed on a semi-empirical basis using the usual relationships derived from continuity, momentum etc. and are described in Appendix A.1.

Linearised Analysis. As per the main propulsion system evaluation a preliminary analysis was undertaken of each sub system comprising the slow speed propulsion system, with the objective of assessing steady state stability margins at designated operating points.

a) Auxiliary Diesel Engine Speed Loop

As was to be expected the results of the hand analysis on the auxiliary engine produced similar equations and results to those obtained on the main speed drive. A review of the frequency response locus leads to similar conclusions regarding stability and parametric sensitivity and provided some marginal improvement in governor control margins.

b) Slow Speed Drive

The small perturbation analysis of the hydrostatic system resulted in the following linearised transfer function:

$$\frac{\Delta N_m}{\Delta \Phi} = \frac{9.55\, K_p N_p D_m Z}{J_t S^2 + \left[\bar{\beta} + \left.\frac{\partial Q_p}{\partial N_m}\right|_{N_{mo}} + Z C_t J_t\right] S + \left[\left(\bar{\beta} + \left.\frac{\partial Q_p}{\partial N_m}\right|_{N_{mo}}\right)(C_t + 9.557) D_m^2\right] Z}$$

This representation implies that stiction effects are negligible and also that propeller torque/speed profile may be considered linear at each operating point. Two load conditions were considered i.e. rated and zero; in each case the sensitivity to changes in the effective bulk modulus of the transmission lines and hydraulic fluid were examined mathematically.

As the performance of an hydraulic system is extremely sensitive to compliance the analysis included both the most pessimistic situation of 100% flexible piping and the more realistic value of 20%.

Figure 17 shows related loci for the open loop response. The effect of pipeline compliance on stability margins is quite pronounced particularly at high flexibilities and low load. In reality all phase margins may be seen to be largely unacceptable suggesting that overall gain should be decreased by as much as an order of magnitude at low load condition. Furthermore, the open loop gain of the system, if not modified, would result in a speed droop of some 35% in the closed loop mode, thereby demanding additional modification and an increase in system complexity.

The results of the hand analysis indicated quite conclusively that specific attention would have to be paid to the slow speed drive system during the simulation process.

c) Bow Thrust System

The bow thrust system equations were linearised at several discrete points throughout the operating range and a continuous relationship between angular displacement and thrust generated. Manipulation of the equations involved produced a transfer function, with variable coefficients. The worst case conditions of compliance were once again utilised in this analysis.

In arriving at the solution several necessary assumptions were made including the neglection of seawater momentum and fluid friction effects in the two arms of the thrust system.

Natural frequency and damping ratio were shown to vary in a totally non linear fashion with load profile suggesting that the demand rate for thrust could be limited by hydraulic compliance constraints rather than overload characteristics.

Simulation Process

As indicated earlier, advantage was taken of the symmetrical layout of the drive system to minimise computer space. Furthermore, the auxiliary diesel engine was relatively unconscious of load and could be reasonably modelled on a linearisation basis about the operating point. The load on this particular diesel was assumed to consist of two slow speed hydraulic pumps, two bow thrust pumps modelled as a single unit, four boost pumps together with associated windage and friction losses in pulse generator, pumps etc. Hydraulic torque could be shown to be a function of displacement, pressure differential and patched accordingly.

Intrinsic to the simulation of the hydrostatic drive system (Fig. 18) were the following non-linearities:-

a) Transmission line leakage

b) Hydraulic fluid and line compliance

c) Relief valve leakage at appropriate Δp (high and low)

d) Torque losses on motor and propeller shafts, and

e) Pneumatic clutch characteristics

Comparison in the steady state between simulation and experimental data indicate that discrepancies were limited to better than 4% throughout the operating range. The linearised analysis previously alluded to proved its value in anticipating dynamic behaviour when evaluated against computed data.

In order to reduce the amount of computing equipment necessary to simulate the propeller and ship and improve the representation of the simulation at low shaft speeds, a new model of the propeller and ship dynamics was derived for use with the slow speed drive.

From the graphs of K_T^1 and K_Q^1 against J^1, used for the propeller simulation graphs of torque and thrust against shaft RPM were plotted with ship speed as a parameter. Wake fractions and thrust deduction factors obtained by experiment were also incorporated in these curves.

For ahead shaft RPM, these curves could be adequately represented by the equations:-

$$\text{Thrust } T = KN_s^{3/2} + KN_s \left(\frac{N}{N_{sMax}} - \frac{V_s}{V_{sMax}} \right) - KV_s \qquad \text{.......... 1}$$

$$\text{Torque } Q_p = KN_s^{2} + KN_s \left(\frac{N}{N_{sMax}} - \frac{V_s}{V_{sMax}} \right) - KV_s \qquad \text{.......... 2}$$

These equations being valid for ship speeds and shaft speeds corresponding to slow speed manoeuvres only.

For astern revolutions and ahead ship speeds, the propeller thrust and torque could each be represented by a single non-linear function plus a constant which was related to both ship and shaft speeds in the operating range under consideration.

The ship resistance characteristic was derived from experimental data applicable to the deep hull condition and the mass of entrained water was assumed constant at 100 tons. The simulation was not valid for astern ship speeds.

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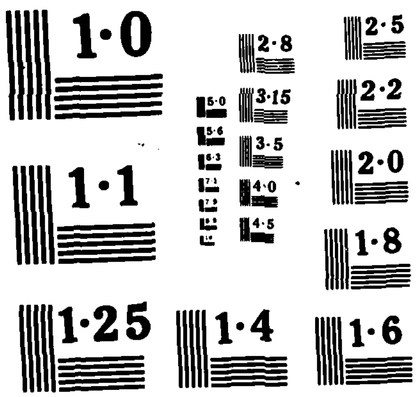
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A complete patch diagram of the propeller and ship simulation is shown on Fig. 16.

Results

Main Propulsion System Simulation. As previously stated, control system evaluation was completed using the deep hull configuration. Ship and machinery performance was then examined for "Clean Hull, ½ Fuel" and "Maximum Towing Resistance" configurations to ensure that control system and hardware limitations throughout the operational envelope of the vessel were fully understood.

1. Control Schemes Investigated

A preliminary manoeuvre evaluation was carried out for the following control system alternatives using the "deep" hull:-

Control Scheme (1):- (Fig. 20 (a))

Set speed rate limitation; clutch sequencing by H.C.U. -

i.e. clutch engage selected for set speed demands above idle; set speed at governor held at idle until clutch pressure is high.

Control Scheme (2):- (Fig. 20 (b))

As Scheme (1) plus clutch disengage from ahead, inhibited for fuel rack setting below specific value.

Control Scheme (3):- (Fig. 20 (c))

Set speed rate limitation and clutch selection as in Scheme (1). H.C.U. detents deleted. Tacho-generators, mounted on clutch input and output shafts, sense clutch state accurately. Clutch state signal controls set speed servo.

An additional control option involving isochronous control of propeller shaft speed was also considered. This option, which could be added to each of these schemes, was given only a superficial evaluation since it was made clear early in the programme that "precise" control of shaft RPM did not offer significant operational advantages. Comments offered on isochronous shaft speed control are, therefore, included for general interest only.

2. Evaluation of Patrol and Cruising Manoeuvres

From a preliminary evaluation of the main propulsion system simulation it became clear that the most severe manoeuvre, in terms of control system and machinery performance, was the Ahead-Astern manoeuvre from maximum ship speed.

Figures 21, 22 and 23 show ship and machinery performance for Control Scheme (1) for different set speed rate limits.

To promote a full understanding of the dynamic performance aspects of ship and machinery during the Ahead-Astern manoeuvre, the curves shown on Fig. 21 have been divided into sections, each of which are described below:-

Section (a):- The manoeuvre commences at the beginning of this section with the control lever (not shown) moving from full ahead to full astern. The set speed servo reduces set speed at maximum rate until idle speed is reached. The ahead clutch remains engaged, hence, propeller shaft speed is reduced along with engine speed. Approximately midway through this section, the propeller torque changes sign and begins to drive the engine. The maximum power that the engine can absorb under these conditions is assumed to be the 'hot engine motoring power'. At the end of this section the fuel rack is at minimum (zero fuel) setting and the negative engine torque plus the shaft friction balances the propeller driving torque induced by the ship's forward speed.

Section (b):- The ahead clutch disengages as idle set speed is reached by the set speed servo. Engine load torque becomes zero and engine speed reduces towards idle. The propeller shaft is now free and driven by the propeller driving torque and shaft friction. The shaft speeds up slightly until equilibrium is reached. As soon as the ahead clutch disengages, the astern clutch is selected. 0.8 seconds after selection, slipping torque is applied to the propeller shaft in the astern sense.

Section (c):- Simultaneously, set speed begins to increase astern. The clutch slipping torque is applied to the engine and shaft causing the engine speed to droop momentarily and the shaft to accelerate through zero towards the astern speed required by the engine. The governor is required to move the fuel rack at almost maximum rate to meet this demand. Power absorbed by the clutch during this phase is initially very large reducing quickly as clutch input-output speed difference becomes smaller.

Section (d):- As propeller shaft and equivalent engine speeds come into line the clutch locks and the transmitted torque falls to that demanded by the propeller. The engine continues to accelerate in response to the increase in set speed. Due to the high astern torque required by the propeller, the governor output remains on the fuel rack limit throughout this section.

Comparison of the response curves of Figs.21 , 22 and 23 shows that the main effects of set speed rate variation are:-

i) Astern clutch absorbed power increases as set speed rate increases;

ii) governor output maximum rate increases as set speed rate increases;

iii) engine underspeed during astern clutch engagement is reduced as set speed rate increases beyond the response capability of the engine;

iv) ship ahead reach reduces with increasing set speed rate.

In this particular installation large transient loads are imposed on the engine during the clutch engagement phase. Even so the simulation shows that minimum engine speeds can be kept to sensible values under the most severe manoeuvres.

Control Scheme (2) which was designed to protect the astern clutch during ahead-astern manoeuvres was investigated with the micro-switch in the fuel rack linkage set to hold in the ahead clutch until the fuel rack exceeds 103.75°. Figures 24, 25 and 26 show the responses obtained for ahead-astern manoeuvres identical to those presented for Scheme (1).

It can be seen that the "Windmilling" period is sustained for a much longer period before the ahead clutch is disengaged and astern clutch selected. The effect on performance is to extend ahead reach by about 30% with a simultaneous and proportional reduction of power absorbed by the astern clutch. Fig. 27 shows the ship and machinery performance trends for the Ahead-Astern manoeuvres shown for both Scheme (1) and Scheme (2) control system configurations. The 100% scale values on the graph selected are arbitrary and bear no relationship to operational limitations or targets. The governor fuel rack design maximum rate is equivalent to full rack travel in 0.3 second (i.e. 143° rack/second). Maximum governor output rate is not exceeded with control scheme (2), however, ship ahead reach is significantly greater than with Scheme (1). Because of the large clutch torque capacity in relation to the engine rating maximum absorbed power was not considered a limitation, a slipping time limit being accepted as the only serious constraint on clutch operation. It can be seen from the response curves that slipping times under all conditions are small and, hence, clutch power loss was not considered to be a critical parameter. An effort was made, however, to reduce the severity of the engagement phase without incurring the loss in ship performance that occurred with Scheme (2). In this scheme (Control Scheme 3) clutch state was measured by comparing clutch input and output speeds. Set speed was then held at idle, following clutch select, until the propeller shaft had accelerated up to the equivalent of clutch speed. Fig. 28 shows the full ahead-full astern manoeuvre using Control Scheme (3) together with a '5 second' set speed rate. No significant change in clutch power loss or total energy absorption was obtained. The main points of difference between the Scheme (1) and Scheme (3) response characteristics may be seen to be:-

i) the time delay following astern clutch selection is increased from the 0.8 second associated with the cam detent plungers to about 1.4 seconds;

ii) the engine underspeeds by a further 10%.

It would appear that holding back set speed until the astern clutch locks contributes to a significant engine underspeed. No improvement in engagement phase performance is evident from the response curves.

Of the above three control schemes, the most acceptable in terms of ship and machinery performance was considered to be Scheme (1) with a "5 second full ahead to idle" set speed rate limit. This rate was selected to give the most favourable ship performance (i.e. minimum stopping distance) compatible with maximum governor output rate capability. Using this selected control system configuration various manoeuvres were then evaluated covering the complete operational envelope for the Patrol, Cruising and Minesweeping roles.

For the deep hull, Ahead-Astern manoeuvres from a number of initial ship speeds were recorded. Figs. 29, and 31 show Ahead-Full Astern manoeuvres from 75%, and 50% maximum speed respectively. As ship speed during the astern engagement phase decreases, the power absorbed by the clutch reduces.

Full ahead-half astern and full ahead-stop manoeuvres are shown on Figs. 32 and 33 respectively for the deep hull. An assessment of the effect of minimum hull resistance was obtained by repeating the Full Ahead-Full Astern manoeuvre for "clean, ½ fuel" hull conditions. This manoeuvre is shown on Fig. 34. The higher windmilling propeller speeds result in a significant increase in clutch power absorption and ahead reach is increased.

Acceleration manoeuvres were investigated for both deep and "clean, ½ fuel" hull conditions. Figs. 35 and 36 show crash acceleration manoeuvres from zero initial ship speed for high and low resistance hull configurations.

The most severe acceleration manoeuvre is from the ship stopped initial condition since propeller torque, at any given shaft speed, reduces considerably as ship speed is increased. Therefore engagement transients at low ship speeds may be expected to show a tendency to increased severity. It is interesting to note, however, that in all cases the ahead clutch power losses are less than in comparable deceleration manoeuvres.

During part of the acceleration phase the governors operate on the fuel rack limit with the engine delivering rated torque until ship speed has built up to about 60% maximum speed. At this point propeller torque begins to reduce towards the steady state value associated with full ahead ship speed. Figure 37 shows a maximum acceleration manoeuvre commencing with the machinery operating at full astern revolutions. Initial ship speed is arranged to ensure a minimum ship speed of 0 Kts. during the manoeuvre. This was necessary since ship resistance and propeller data were not available for astern ship speeds at commencement of simulation.

3. Minesweeping Manoeuvres

Ship and machinery performance during minesweeping manoeuvres was investigated for the selected control system design (i.e. Scheme (1) with "5 second idle-full ahead" rate). To ensure the most severe machinery loading the maximum resistance sweep configuration was incorporated. To enable assessment of "streaming" and "heaving in" performance, total sweep resistance was computed separately from the ship resistance. Fig 38 and 39 show slam acceleration manoeuvres from 25% and 40% speed respectively with sweeps in tow. Clutch power absorption values are small due to the significant ahead way present during the engagement phase.

Following clutch engagement, the fuel rack quickly reaches a position corresponding to maximum governor output setting where it remains for the duration of the manoeuvre.

Streaming and heaving in manoeuvres were simulated for the same sweep configuration, as was the affect on performance of manoeuvring with only one engine operational under the duress of the selected control system scheme. No adverse effects on machinery loading were observed. Fig. 40 shows a slam acceleration manoeuvre under single engine power with maximum towing resistance and although this manoeuvre is unrealistic in terms of normal operating practice, it does represent the most pessimistic loading conditions.

It can be seen that engagement transients are no more severe than with two engine manoeuvres and that the governor provides the necessary engine overload protection by limiting fuel rack to an equivalent developed torque approaching the maximum allowed. Ship speed levels out at about 50% maximum in this particular configuration.

4. Isochronous Shaft Speed Control

Some consideration was given to the possibility of introducing isochronous shaft speed control into the control system design. A brief evaluation of the simulated system showed that pure integral control of shaft speed was adequately stable provided that a low integral gain coefficient was utilised. It was, therefore, considered feasible to provide a limited authority trimming system which could be switched IN and OUT on the control consul. This technique would ensure that component failure during closed loop operation would not result in an unacceptable failure mode and that normal droop speed control could be recovered by switching out the isochronous control mode. The control scheme suggested is shown in Fig. 41

The authority limit required to allow isochronous control of shaft speed during normal Patrol and Cruising operation would be about 25 shaft rpm.

Auxiliary Propulsion System Simulation Results. The ship was subjected to simulated trials essentially divided into three distinct categories:-

i) slow speed drive manoeuvres with bow thrust system developing zero thrust (both port and starboard valves open);

ii) bow thrust manoeuvres with slow speed drive at each of two conditions:-

a) ship stopped

b) ship full ahead

iii) combined slow speed drive and bow thrust manoeuvres, emphasising simultaneous load demands on diesel engine.

Control Schemes Investigated

Auxiliary Diesel Engine. The control philosophy for the auxiliary diesel engine speed loop is prescribed by the choice of governor, which has been selected as a proportional governor possessing 6% droop characteristic. Since elimination of this steady state error would appear to offer no significant operational advantages, proportional control is the only scheme to be assessed for the engine speed loop.

Slow Speed Drive. The results of the linear analysis indicated that proportional control of shaft speed would prove inadequate, indicating in turn that an additional degree of complexity would be required for closed loop control. From consideration of operational requirements and the tendency to decreased reliability of more sophisticated schemes, it was decided that an open loop control scheme should be investigated. In particular, the effect of variation of the rate of hydraulic pump swash plate movement needed to be evaluated, using both the system bulk modulus applicable to both a 100% and 20% flex pipe transmission system. Additionally, the effect of pneumatic clutch operation on both auxiliary diesel engine and slow speed drive performance required investigation.

Bow Thrust System. The general control system philosophy for the bow thrust system was developed during the preliminary evaluation phase of the programme which was completed prior to integration of the Bow Thrust simulation with the auxiliary diesel and slow speed drive system and may be summarised as follows:-

Thrust changeover from port to starboard, or vice versa, in approximately the same time as the vessel's rudder response, i.e. 12 sec. whilst ensuring that valve generated noise and valve spindle torques were kept to a minimum.

Preliminary work, using hydraulic compliance data equivalent to 100% flexible pipe, indicated that this specification could be met using a valve rate (open to closed) of 7 seconds and a swash actuator rate of 3.5 degrees/second by the use of the following sequence:-

i) reduce centrifugal pump speed via swash plate lever;

ii) changeover divertor valves;

iii) increase centrifugal pump speed.

Valve spindle torques and noise levels associated with this manoeuvre were calculated off-line and performance optimised in this respect until acceptable values were obtained. The significant point noted from this initial work was that changing over the divertor valves with low differential pressure results in both minimum noise and spindle torque. The result of rigorous enquiry indicated that a 10% flexible pipe configuration would be more representative of a physical system and all subsequent simulated trials were undertaken with the corresponding value of compliance included.

From the preliminary evaluation described briefly above the following control system philosophy was established.

i) Open loop control only is necessary; closing the loop around either thrust itself or any intermediate pressure (e.g. centrifugal pump speed or pressure) offered no significant advantages in response or accuracy.

ii) In the zero thrust condition the centrifugal pump should run at approximately 45% maximum revs. or less with both divertor valves open, thus minimising the possibility of inadvertent blockage of the thrust nozzles or pump inlet.

iii) Divertor Valve and swash actuator would require further investigation to establish sensible system performance characteristics and limitations.

iv) A logic system would be required to ensure satisfactory operation of the system during the entire range of manoeuvres. It was assumed that some form of position transducer would be required to sense when finite (say 5%) demand for thrust has been made to port or starboard - this instruction to be "remembered" when this minimum level of demand had been exceeded.

The following resulting logic statements required implementation:-

Open port valve if:-

Centrifugal pump speed low AND less than 5% starboard demand.

Close port valve if: -

Centrifugal pump speed low AND NOT less than 5% starboard demand.

Open starboard valve if:-

Centrifugal pump speed low AND less than 5% port demand.

Close starboard valve if:-

Centrifugal pump speed low AND NOT less than 5% port demand.

Increase swash if:-

Port valve closed AND starboard valve open,

OR starboard valve closed AND port valve open.

Simulation of Minehunting Manoeuvres

Slow Speed Drive. The evaluation of the performance of the slow speed drive system and the auxiliary diesel engine during slow speed drive manoeuvres has been completed for the bow thrust system developing zero thrust with both divertor valves open and the centrifugal pump running at 45% maximum RPM.

Preliminary examination of auxiliary propulsion system performance indicated that two operational conditions warranted particular attention, i.e.:-

i) maximum transient loading of the slow speed drive system and auxiliary diesel engine;

ii) oscillatory behaviour of the slow speed drive system at low swash angles (as predicted by linear analysis).

It was observed that the former condition occurred during slam acceleration manoeuvres from low ship speeds. Recordings of the system acceleration performance from the ship stopped condition are shown in Fig. 42 assuming a bulk modulus applicable to 20% flexible pipe in the hydraulic transmission lines.

The auxiliary diesel governor set speed was arranged to give rated rpm at the condition of maximum bow thrust and shaft speed. Thus, the initial condition for the manoeuvre shown corresponds to a higher engine speed due to reduced diesel loading i.e. only losses are being supported initially.

As the slow speed drive demand is increased the propeller shaft speed follows at the same rate. Propeller torque is generated and is reflected via the hydrostatic drive as an auxiliary diesel engine load. This causes the engine speed to fall to a minimum at maximum developed torque when the actuator movement is halted.

From this point, torque begins to decline as the ship gains speed, thereby allowing the engine speed to recover to a new steady state level.

As may be expected, the most severe transients are imposed at the higher swash rates since, in this case, load is quickly applied to the system. It may be noticed however, that even in the worst case the high line pressure is restricted sensibly by the cross-line relief valve. Subjection of the vessel to a similar manoeuvre when fitted with totally flexible transmission lines indicated that resultant machinery response was little altered although line pressure transients showed a distinct frequency shift, as was to be expected. A complete sweep of servo-rates -v- ship acceleration indicated a trade off situation between response and maximum torque.

A five fold increase in servo rate resulted in a reduction in time to rated sweep speed of approximately 15% with a corresponding increase of measured maximum torque a little under 10%.

Consideration of the conditions leading to oscillatory behaviour of the slow speed drive system revealed that the worst case occurred during manoeuvres from high propeller speeds to speeds. As predicted by linear analysis the case corresponding to 100% flexible pipe transmission lines exhibited the most severe oscillations as illustrated in Fig 43.

Evaluation of the response indicated that the relative stability decreases This occurs as a result of the negative slopes of the propeller torque/speed/ship speed characteristics at low shaft speeds and high ship speeds. The high servo rates exhibit the most severe oscillations because low shaft speeds are achieved before the ship has decelerated appreciably, so that the steepest negative load slopes are encountered.

Fiq. 44 shows the system response during a similar manoeuvre but with the bulk modulus applicable to a 20% flexible pipe transmission system. The increased stiffness and damping provided by the transmission system eliminates the oscillation due to negative propeller load slopes and satisfactory transient performance is obtained.

The linear analysis completed earlier suggested that the least stable condition would occur during manoeuvres. However, the effect of closing the hydraulic pump to flow at zero prevents the transmission of pressure transients in the hydrostatic system and therefore reduces transient oscillations. This effect is illustrated in Fig. 45 which show the system performance during this manoeuvre.

The recordings described above are sufficient to allow evaluation of system performance in those modes which are most likely to give rise to adverse operational conditions. However, for the sake of completeness, a selection of recordings of the system response during other manoeuvres were evaluated.

These included crash stop manoeuvres from full ahead ship speed, crash stop manoeuvre from half ahead speed with ship decelerating under full astern swash, slam acceleration from 25% speed etc.

Fig. 46 provides an indication of system response during slow speed drive clutch engagement manoeuvres. In order to include the most severe case with respect to transient power absorption for the clutch, an engagement manoeuvre was completed for the ship and propeller operating at full ahead with the hydrostatic drive running full astern as shown. Under these conditions the maximum speed difference exists between clutch driven and driving plates. It can be seen from Fig. 46 that, at the instant of initiation of clutch engagement, the speed of both plates commences a decreasing transient excursion. The propeller speed traverses into the astern region and clutch locking occurs when shaft is rotating nominally astern. The coupled shafts then accelerate astern as demanded.

During this manoeuvre the imposed load torques must be satisfied by the auxiliary diesel engine.

Bow Thrust System. Performance of the bow thrust system was assessed by subjecting it to a series of manoeuvres entailing combinations of divertor and swash plate actuator rates, e.g.:-

i) Crash demand for maximum thrust with ship running full ahead

ii) Crash demand for maximum thrust with ship stopped

iii) Maximum thrust reversal from port to starboard with ship running full ahead

iv) Maximum thrust reversal from port to starboard with ship stopped

Fig. 47 provides an example of the results obtained, when the system is subjected to maximum actuator rate, full thrust reversal at ship full ahead.

Overall performance may be summarised as follows:-

1. Unidirectional crash demand for bow thrust resulted in an immediate but small increment of lateral thrust due to divertor valve slamming, followed by a build up to maximum thrust at a rate proportional to swash plate rate.

2. Small percentage overshoot occurred due to interaction of hydraulic drive and diesel speed control dynamics.

3. In the ship stopped condition the system demonstrated an increase in oscillatory motion over ship full ahead as the auxiliary engine transient speed changes were no longer damped out by the high load/slope propeller characteristics associated with the higher ship speeds.

4. Overall thrust reversal could be obtained quite smoothly with accumulated transients well within engine rated capability.

5. In all cases diesel torque and speed overshoots/undershoots were all a function of demand rate and were largely unaffected by choice of divertor valve rate.

Combined Manoeuvres. The purpose of this section was to evaluate the performance of the auxiliary diesel engine during simultaneous transient loading from both the slow speed drive and the bow thrust systems. From the previous investigations on bow thrust and slow speed drive manoeuvres the worst case loading conditions on the auxiliary diesel engine were selected, i.e. slam acceleration from ship stopped simultaneously with maximum bow thrust demand. Examination of the responses indicated that peak transient torques for slow speed drive manoeuvres occurred after initiation, while for the bow thrust system Fig 48 shows system performance for slam acceleration from ship stopped with maximum bow thrust demand applied for 2½ seconds.

It can be seen that the simultaneous demand for engine torque from both systems caused the fuel racks to open fully so that the developed engine torque quickly reached a maximum. This was insufficient to support the required load torque and the engine exhibited a speed reduction until load torques were balanced.

This transient drop in engine speed caused the bow thrust and propeller shaft speed to decrease, recovery of these variables being delayed until the vessel accelerated.

Further trials using other combinations of ship propulsion and bow thrust demand indicated that the above situation represented the worst case condition with no latent surprises.

GENERAL CONCLUSIONS

1. Main Propulsion System

Briefly, the results of the study indicated that some attention would have to be paid to governor output rate capability and general speed of response in order to cope with engagement transients and stability at low power. Furthermore, substantial clutch power absorption transients occur during crash stop manoeuvres as a result of initially, high engine idle speeds creating, in turn, large speed differentials between shafts. Large clutch slipping torques add to the problem and in consequence some modification to maximum clutch hydraulic pressure and associated rate could provide considerable improvement. Limitation of maximum pressure carries with it the penalty of reduced crash stop performance i.e. reduced maximum astern torque capacity and hydraulic rate control adds to the complexity.

Examination of the Full Ahead - Full Astern manoeuvres using the "hold in ahead clutch" control scheme, reduces the free shaft r.p.m. by some 40% and hence reduces power absorption requirements. A shaft braking system could provide the optimum solution. Acceleration manoeuvres were found to be relatively insensitive to control system configuration with engagement transients being markedly reduced due to relatively small initial engagement shaft differentials.

2. Auxiliary Propulsion System

Slow Speed Drive. No significant problems were identified in the study - simple open loop proportional control appears to be adequate to meet sensible operational requirements. The phenomenon of 'windmilling' induced shaft speed oscillation was identified as a potential hazard should hydraulic compliance be permitted to fall below permitted minima particularly at small swash plate movements.

Bow Thrust System. Although many control options were considered at the commencement of the programme with respect to magnitude and direction of thrust, conclusions reached indicated that the most acceptable approach was the simplest in concept and configuration. Results were as follows:-

a) Sea water discharge pressure provides adequate indication of initial magnitude of thrust.

b) Open loop scheduling of divertor valves and hydraulic pump give satisfactory control system characteristics provided that hydraulic system is well designed in terms of compliance and boost system operation. Some shaping of the relationship between control lever movement and actuator movement may be required if a linear thrust characteristic is desirable.

c) The noise generated in any one valve during a thrust reversal may be kept within acceptable limits by the control system investigated.

d) Thrust response is well within the operating envelope defined by vessel sea keeping characteristics and may be tailored to suit all requirements considered.

3. Combined Slow Speed Drive

Although the performance characteristics of the auxiliary engine were similar to that of the main engine the smaller total connected shaft inertia results in faster dynamic response thereby reducing governor gain requirements to ensure adequate stability.

Detailed investigation of the results indicated that during slam acceleration manoeuvres (the 'worst' case) on the slow speed drive system with maximum bow thrust generation the engine developed torque may be insufficient to meet requirements at rated RPM and consequently a period of sustained underspeeding may occur. Engine speed recovers as transient propeller torques reduce.

The investigation also highlighted the dependence of hydrostatic system performance at low propeller shaft speeds and 'high' ship speeds on effective compliance suggesting the need for adequate and sensibly placed bleed points.

Clutch absorbed torques could be minimised without detriment to overall ship performance by running up slow speed drive motor to propeller shaft speed prior to the initiation of engagement.

CONCLUDING COMMENTS

The above study proved to be an interesting excursion providing insight into problems confronting potential M.C.M.V. shipbuilders. It also exercised the minds of many and emphasised the benefits to be gained from applying simulation techniques at an early stage in concept development.

APPENDIX A.1

1. Linearised Analysis of Engine Speed Control Loop

Using steady state data obtained from physically testing the relevant engines a series of power, speed fuel rack permutations were derived leading to use of simplified equations of the form:-

$$Q_e = K(10^5/N_e + 14)X_f - 1.22 \times 10^7/N_e \quad .... 1$$

$$Q_e - Q_L = (2\pi/60)\ J.DN_e \quad .... 2$$

$$X_f = K_x\ (N_{se} - N_e)\ \{G(s)\} \quad .... 3$$

where Q_e = Engine developed torque

Q_L = Engine load torque

J = Inertia referred to crankshaft

X_f = Fuel rack setting

K_x = Governor gain

N_e = Crankshaft R.P.M.

N_{se} = Governor set speed

$\{G(s)\}$ = Governor Dynamics

All engine, clutch and gearing losses were included in the derived equations.

2. Propeller and Ship Dynamics

Data was rearranged in the form of K_T^1 and K_Q^1 -v- J^1 for ahead and astern rotation resulting in the derivation and use of the following equations:-

$$\text{Torque } Q = K_Q^1.\rho.D^3\ \{(n_s^2.D^2. + (V_s(1 - K_w))^2\}\ /g \quad .... 4$$

$$\text{Thrust } T = K_T^1.\rho.D^2\ \{(n_s^2.D^2. + (V_s(1 - K_w))^2\}\ /g \quad .... 5$$

where: K_Q^1 = propeller torque coefficient

K_T^1 = propeller thrust coefficient

ρ = density of sea water

D = diameter of propeller

n_s = shaft speed RPS

V_s = ship speed relative to open water

K_w = wake fraction

The simulation took account of thrust loss, due to hull interaction effects, by using the following equation applied to a half ship:-

$$T(1 - K_t) - R = \tfrac{1}{2}M.\frac{dV_s}{dt} \qquad \text{.......... 6}$$

where: T = thrust of one propeller

R = ½ total ship resistance at ship speed V_s

K_t = thrust deduction factor

M = effective mass of ships hull including entrained water

3. Slow Speed Drive

The equations used establish a dynamic model of the slow speed drive system, including the pneumatic clutch are shown below and invoke the usual assumptions associated with flow control servosystems. Additional assumptions include, constant gear box efficiency throughout operating profile, lumped motor and load inertias, linear relief valve characteristics over range of interest, shaft stiction negligible, cavitation non existent etc.

The continuity equations for pump and motor therefore becomes:-

$$q_{ap} = K_p N_p \Phi - C_{ip}(P_a - P_b) - C_{ep}P_a \qquad \text{.......... 7}$$

$$q_{ap} = K_p N_p \Phi - C_{ip}(P_a - P_b) + C_{ep}P_b \qquad \text{.......... 8}$$

$$q_{am} = D_m N_p + C_{ip}(P_a - P_b) + C_{ep}P_a \qquad \text{.......... 9}$$

$$q_{bm} = D_m N_p + C_{ip}(P_a - P_b) - C_{ep}P_b \qquad \text{......... 10}$$

Transmission line equations:-

$$\frac{V_1}{\beta_e}.\frac{dP_a}{dt} = q_{ap} - q_{am} \qquad \text{......... 11}$$

$$\frac{V_1}{\beta_e}.\frac{dP_b}{dt} = q_{bm} - q_{bp} \qquad \text{......... 12}$$

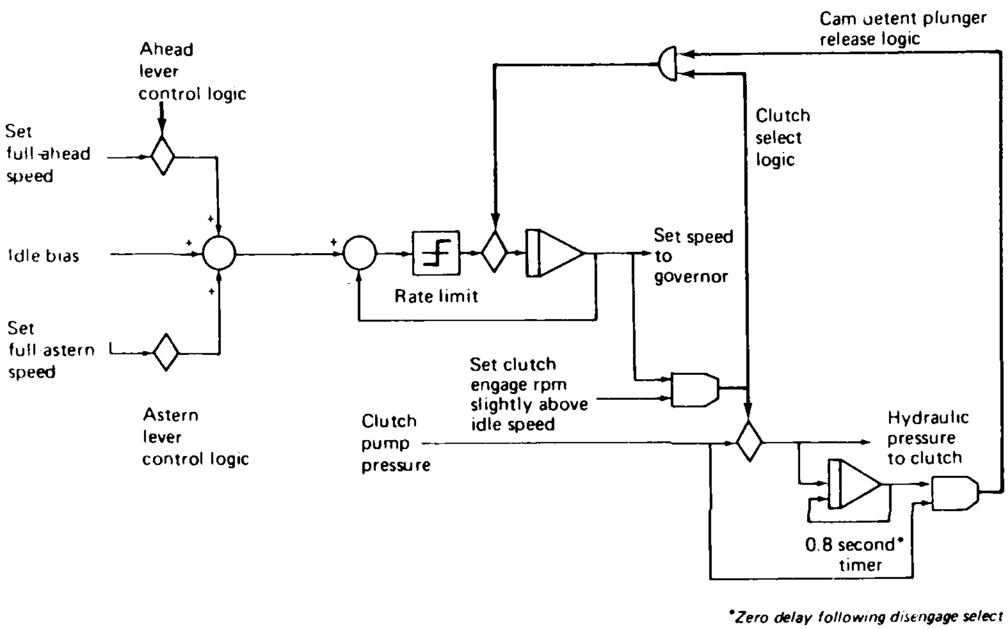
$$\frac{e}{V_1} = fn(P_a) \qquad \text{......... 13}$$

This function was based upon the assumption that 20% of the total transmission line oil volume was contained by flexible pipe.

Relief valve equations:-

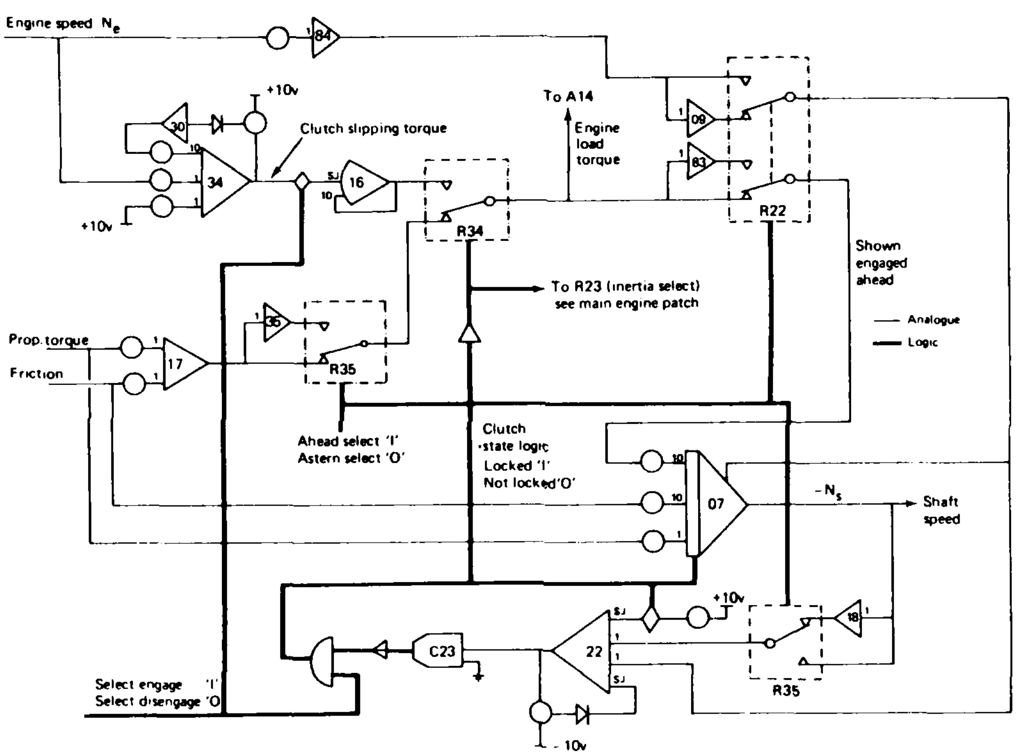
$$q_r = 4.6(P_a - P_b - 3000) \qquad \text{......... 14}$$

$$q_t = 0.226(P_{a/b} - 150) \qquad \text{......... 15}$$



SCHEMATIC OF H.C.U. AND SET SPEED SERVO SIMULATION

FIG. 11



REVERSING CLUTCH PATCH DIAGRAM

FIG. 10

CLUTCH SLIPPING TORQUE vs ENGINE SPEED

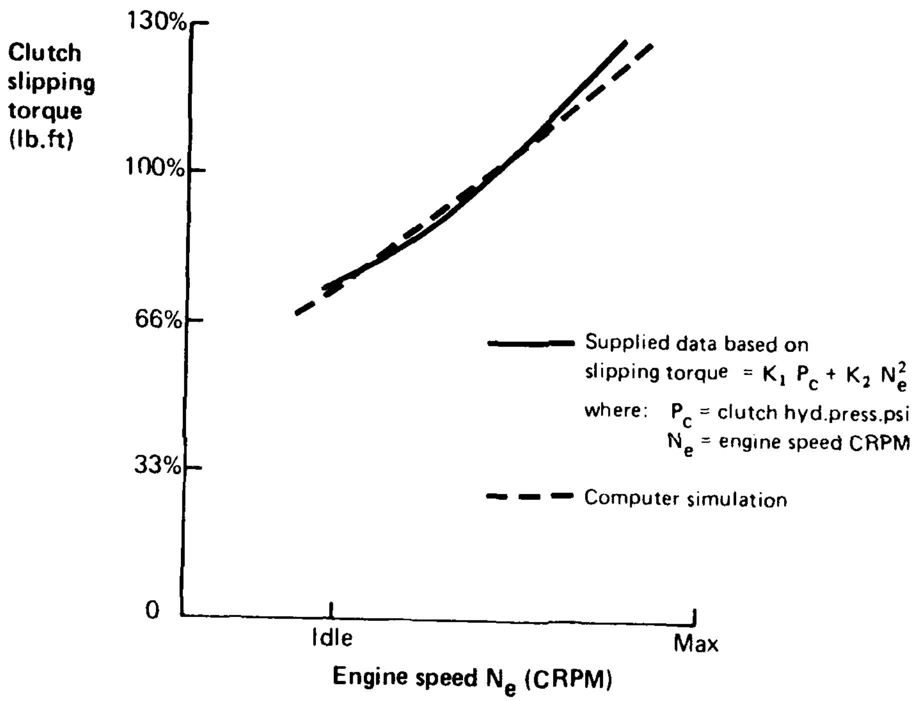
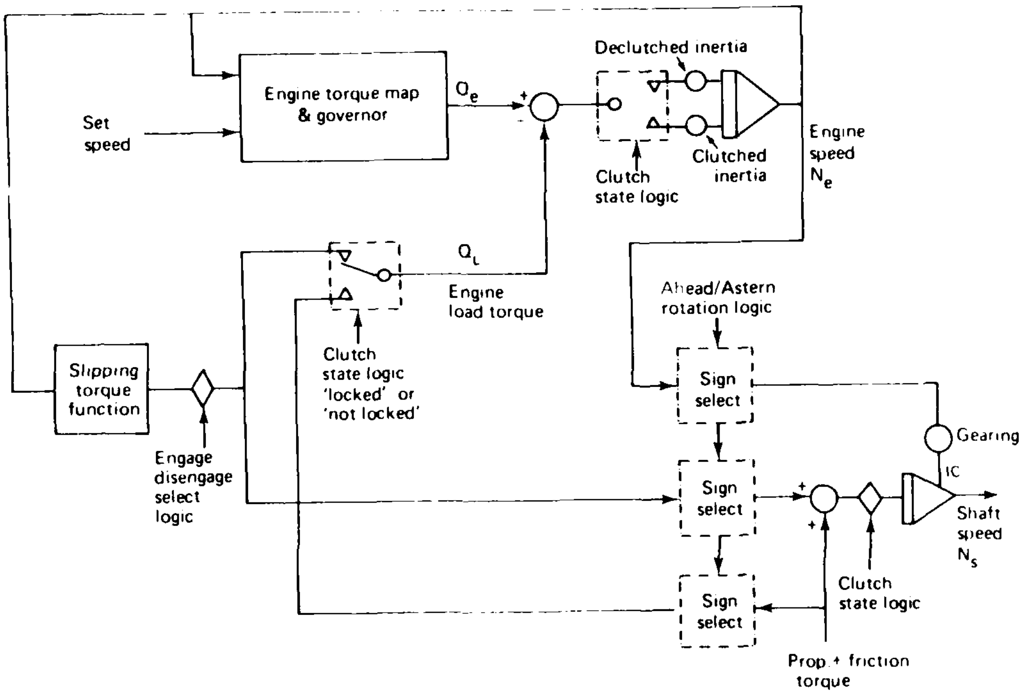
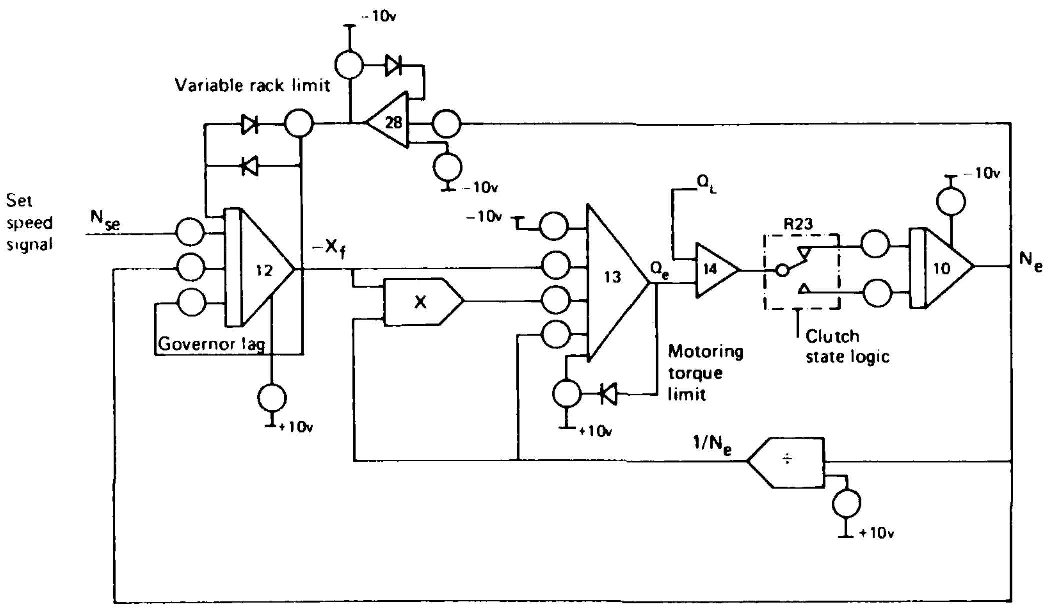


FIG. 9



SCHEMATIC OF REVERSING CLUTCH CONTROL

FIG. 8



MAIN ENGINE PATCH DIAGRAM

FIG. 7

MAIN ENGINE LIMIT CYCLE CHARACTERISTICS

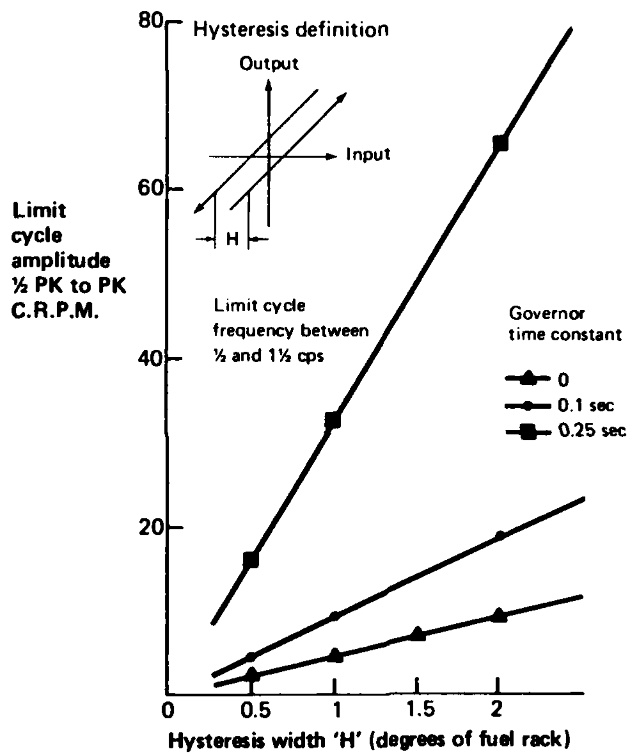


FIG. 6

STABILITY MARGIN vs
GOVERNOR TIME CONSTANT

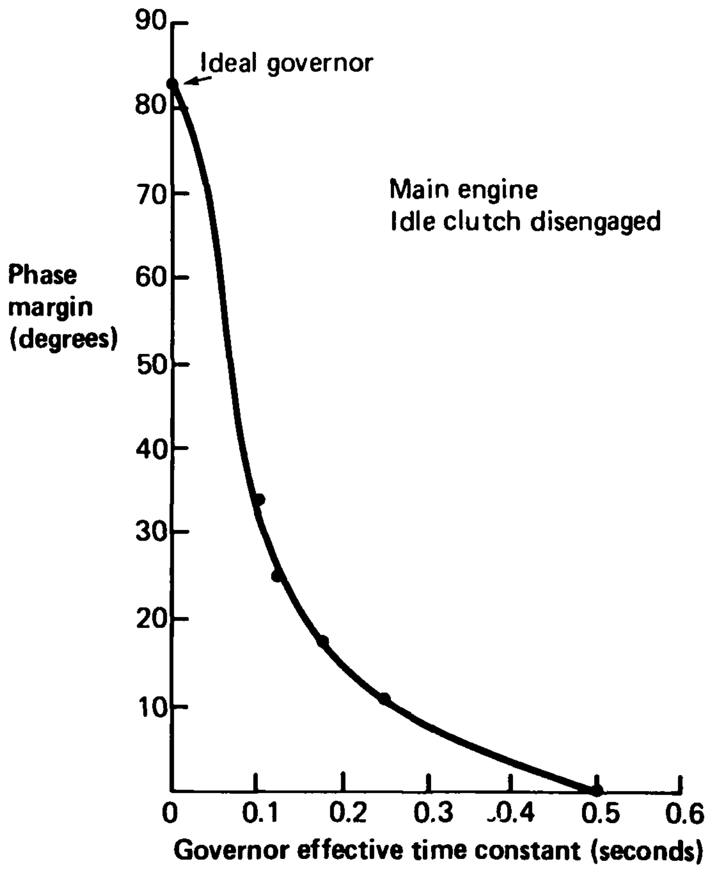


FIG. 5

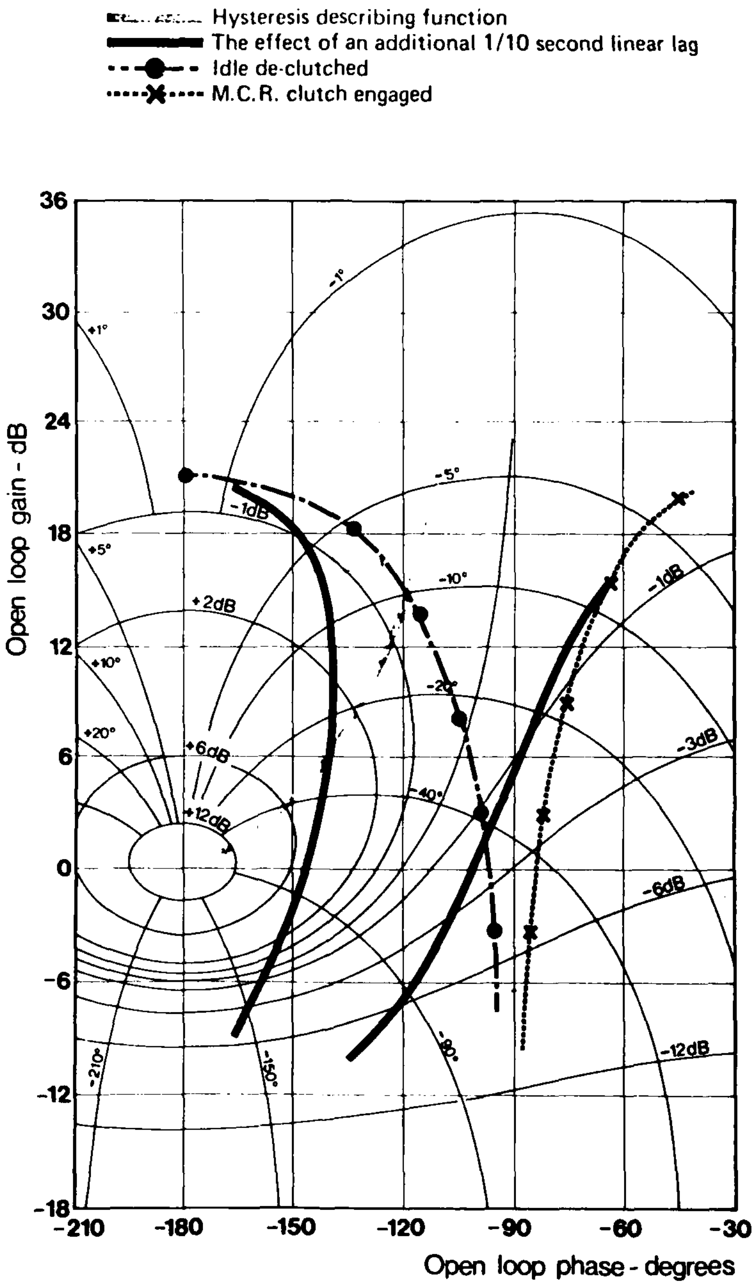

Hysteresis describing function
The effect of an additional 1/10 second linear lag
Idle de-clutched
M.C.R. clutch engaged
Open loop gain - dB
Open loop phase - degrees
36
30
24
18
12
6
0
-6
-12
-18
-210
-180
-150
-120
-90
-60
-30
-1°
+1°
-5°
-1dB
+5°
-10°
+2dB
+10°
-20°
+20°
+6dB
-3dB
-40°
+12dB
-6dB
-12dB
-210°
-150°
-90°

FIG. 4

INTERDEPENDENCE OF THE LINEARISED TERMS

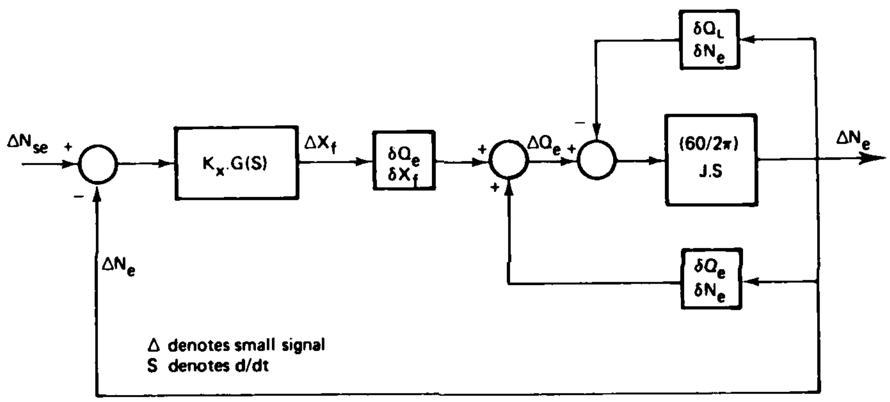
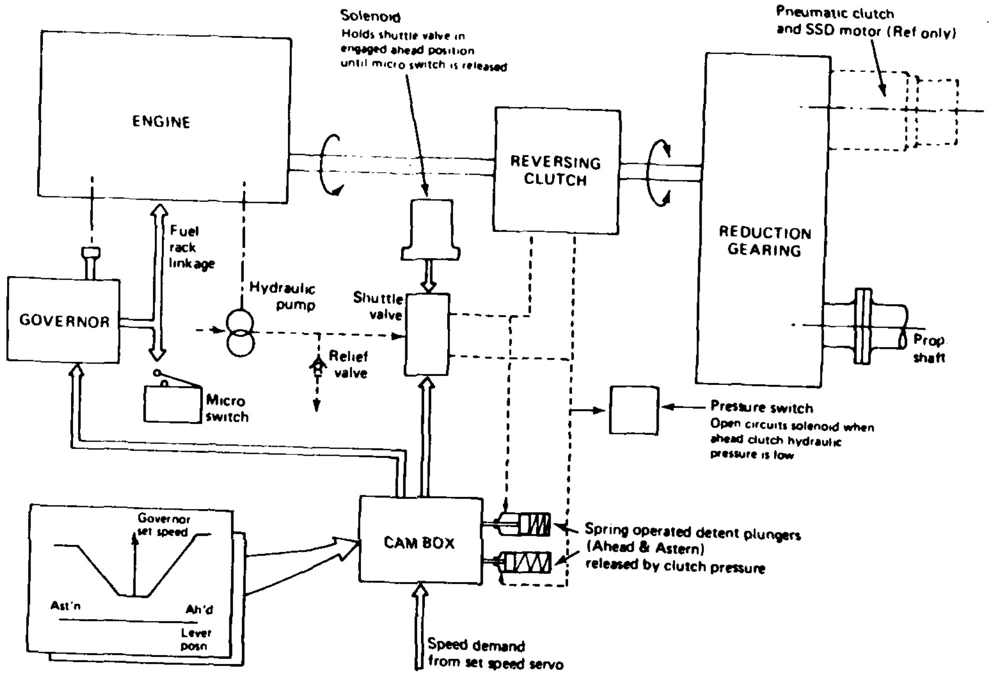
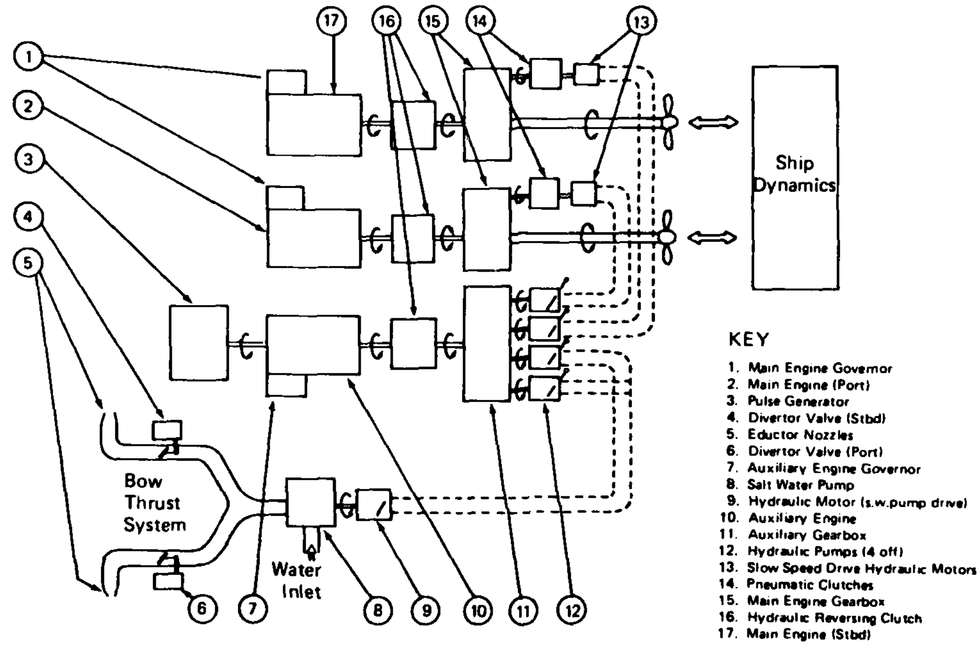


FIG. 3



SCHEMATIC OF ENGINE PACKAGE

FIG. 2



SCHEMATIC DIAGRAM OF PROPOSED MCMV PROPULSION MACHINERY

FIG. 1

APPENDIX A.2

NOMENCLATURE

Propeller and Ship Dynamics

D	=	Diameter of propeller	ft.
J^1	=	Advance coefficient (modified)	
K_q^1	=	Propeller torque coefficient	
K_T^1	=	Propeller thrust coefficient	
K_t	=	Thrust deduction factor	
K_w	=	Wake fraction	
M	=	Effective mass of ship's hull including entrained water	lbf.sec^2/ft.
n_s	=	Propeller shaft speed	R.P.S.
R	=	½ total ship resistance at ship speed Vs	lbf.
T	=	Thrust of one propeller	lbf.
V_s	=	Ship speed relative to open water	ft./sec.
ρ	=	Density of sea water	lb./ft.^{3}

Main Engine

$G(s)$	=	Main engine governor dynamics	
J	=	Inertia referred to main engine crankshaft	lb.ft/sec^2
K_x	=	Main engine governor gain	degrees/CRPM
Ne	=	Main engine crankshaft speed	CRPM
Nse	=	Main engine governor set speed	CRPM
Qe	=	Main engine developed torque	lbf.ft.
Q_L	=	Main engine load torque	lbf.ft.
X_f	=	Main engine fuel rack setting	degrees

Auxiliary Diesel Engine

$G_{a(s)}$	=	Auxiliary engine governor dynamics	
J_a	=	Total inertia referred to auxiliary engine shaft	lbf./ft./sec^2
K_{xa}	=	Auxiliary engine governor gain	degrees/CRPM
N_{ea}	=	Auxiliary engine crankshaft speed	CRPM
N_{sea}	=	Auxiliary engine governor set speed	CRPM

Flow through port and starboard valves:-

$$q_p = q_s = K_6 C_v \sqrt{P_{vp} - (P_{np} \text{ or } P_{ns})} \qquad \ldots\ldots\ldots \; 25$$

Valve flow coefficient:-

$$C_v = f_n (\Phi_e) \qquad \ldots\ldots\ldots \; 26$$

where Φ = respective valve opening in uegrees.

Torque generated by the centrifugal pump:-

$$Q_{cp} = K_7 P_p \, q_o / N_{cp} \, \eta_{cp} \qquad \ldots\ldots\ldots \; 27$$

Invoking the assumptions indicated in the test the equations assumed to represent hydrostatic drive system associated with providing the motive power for the hydraulic pump were as follows:-

Rate of change of pressure in hydraulic line:-

$$\frac{dP_a}{dt} = \frac{\beta e}{V} (K_8 \, \Phi . \, N_p - C_1 P_a - K_q C_1 - K_{10} P_a - K_{11} N_{cp}) \qquad \ldots\ldots\ldots \; 28$$

Hydraulic stiffness (function of Bulk Modulus and line stiffness, configuration etc.):-

$$\frac{\beta e}{V} \quad f(P_a)$$

Rate of change of pump speed:-

$$\frac{d}{dt} N_{cp} = K_{12} P_a - K_{13} N_{cp} - K_{14} Q_{cp} - K_{15} \qquad \ldots\ldots\ldots \; 29$$

Motor shaft torque equations:-

clutch locked condition:

$$\frac{60}{2\pi} D_m(P_a - P_b) - \frac{IN_m^1}{N_m} C_f'(P_a + P_b) - B_m N_m - \frac{60}{2\pi} J_m \frac{dN_m}{dt}$$

$$= 12(B_p N_s + B_t T + Q_p + B_t T + Q_p + \frac{60}{2\pi} J_p \frac{dN_s}{dt})/\eta G \quad \text{......... 16}$$

clutch disengaged condition:

i) Motor Shaft:

$$\frac{60}{2\pi} D_m(P_a - P_b) - \frac{IN_m^1}{N_m} C_f'(P_a + P_b) - B_m N_m - \frac{60}{2\pi} J_m \frac{dN_m}{dt} = 0 \quad \text{......... 17}$$

ii) Propeller Shaft:

$$B_p N_s + B_t T + Q_p + \frac{60}{2\pi} J_p \frac{dN_s}{dt} = 0 \quad \text{......... 18}$$

clutch slipping condition

i) Motor Shaft:

$$\frac{60}{2\pi} D_m(P_a - P_b) - \frac{IN_m^1}{N_m} C_f' (P_a + P_b) - B_m N_m - \frac{60}{2\pi} J_m \frac{dN_m}{dt} - 12Q_c/\eta G = 0 \quad \text{... 19}$$

ii) Propeller Shaft:

$$B_p N_s + B_t T + Q_p + \frac{60}{2\pi} J_p \frac{dN_s}{dt} = Q_c \quad \text{......... 20}$$

4. Bow Thrust System

From momentum considerations pressure at throat of 'Y' piece corresponds to:-

$$P_t = P_p - K_1 q_o^2 - K_2 \frac{d}{d_t} q_o \quad \text{......... 21}$$

Total flow of sea water supplied by pump:-

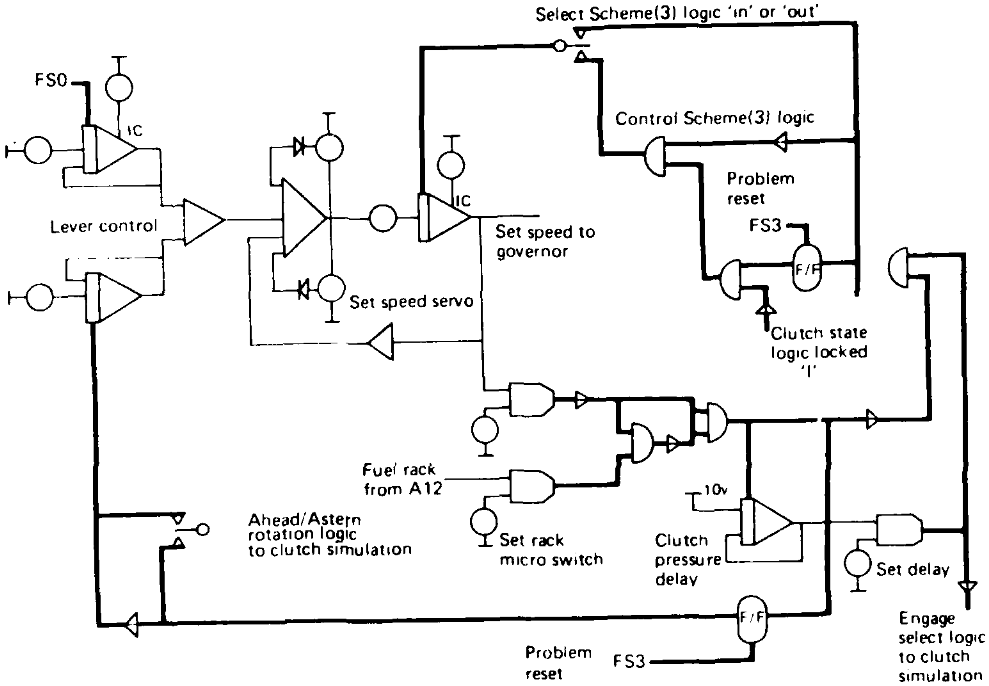
$$q_o = q_p + q_s \quad \text{......... 22}$$

Upstream valve static pressure:-

$$P_{vp} = P_t - K_3 \frac{d}{d_t} q_p - K_4 q_p^2 \quad \text{......... 23}$$

Pressure drop across both port and starboard nozzles:-

$$P_{np} = P_{ns} = K_5 q_p^2 \quad \text{......... 24}$$



CONTROL SYSTEM & H.C.U. PATCH DIAGRAM

FIG. 12

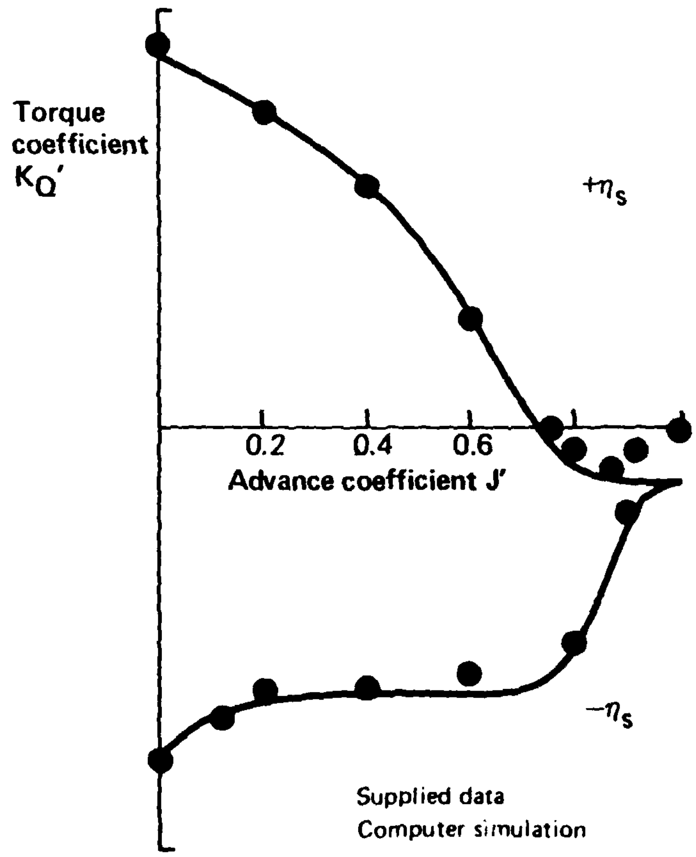
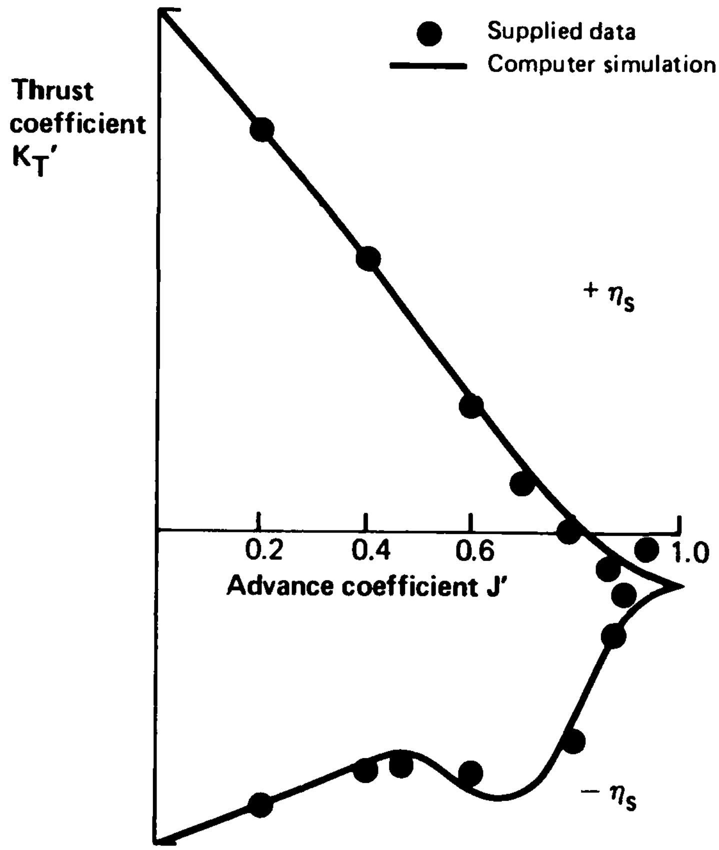

Torque
coefficient
K_Q'
$+\eta_s$
0.2
0.4
0.6
Advance coefficient J'
$-\eta_s$
Supplied data
Computer simulation

FIG. 13



Supplied data
Computer simulation
Thrust coefficient K_T'
$+\eta_s$
0.2
0.4
0.6
1.0
Advance coefficient J'
$-\eta_s$

FIG. 14

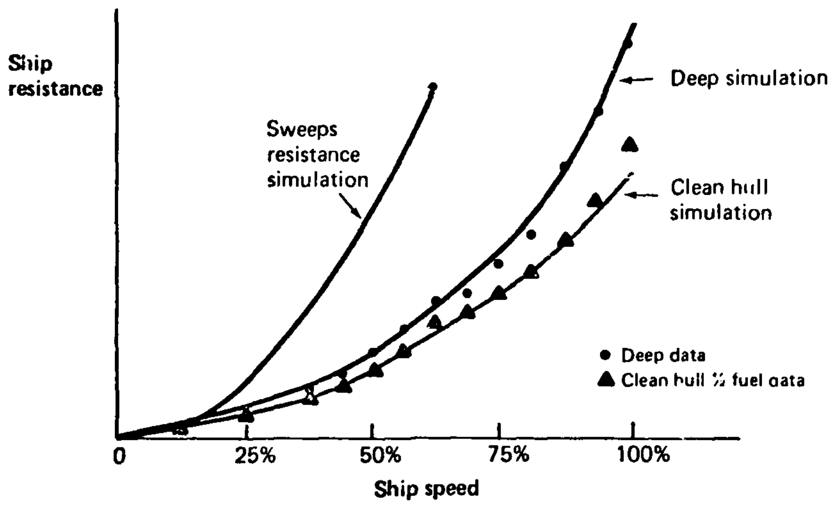
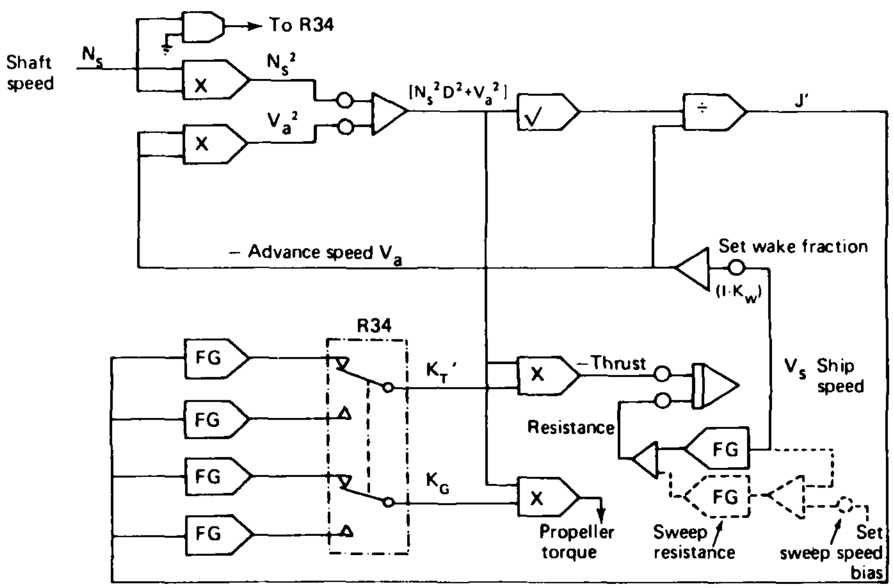

Ship resistance
Sweeps resistance simulation
Deep simulation
Clean hull simulation
Deep data
Clean hull ½ fuel data
0
25%
50%
75%
100%
Ship speed

FIG. 15



PROPELLER AND SHIP PATCH DIAGRAM

FIG. 16

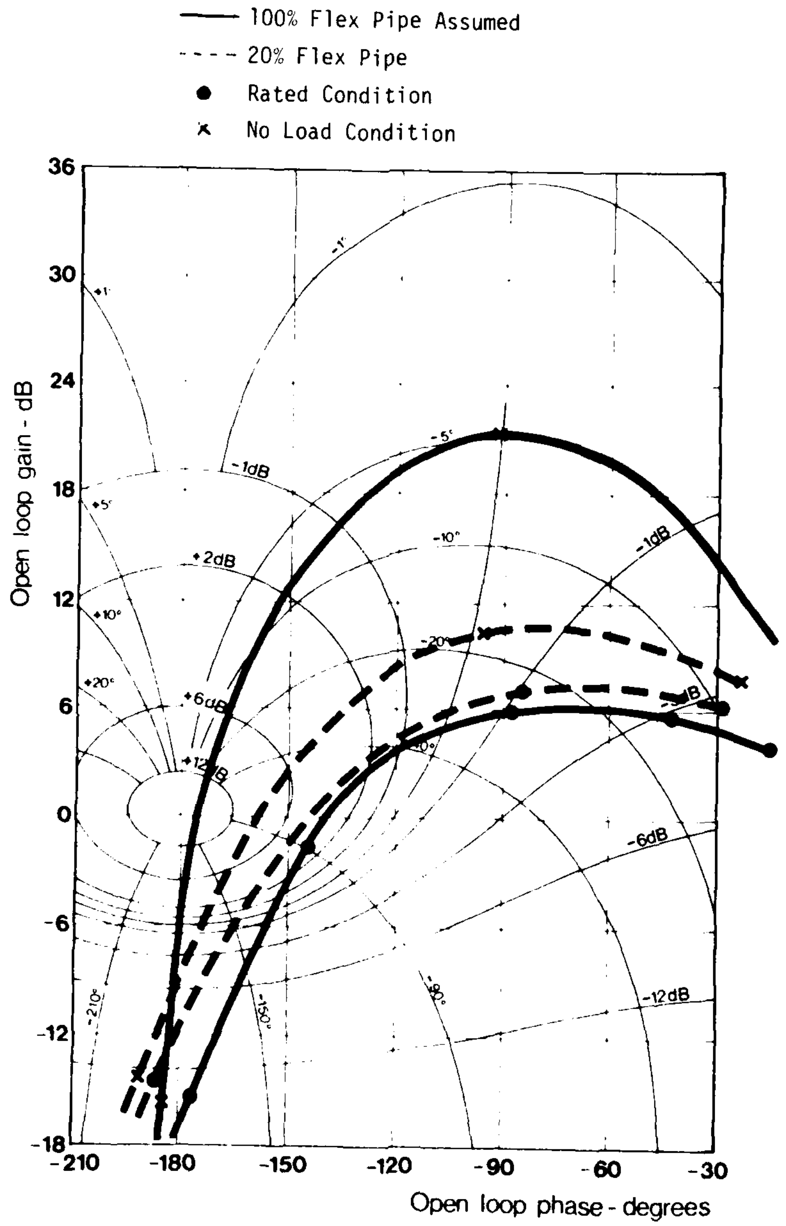
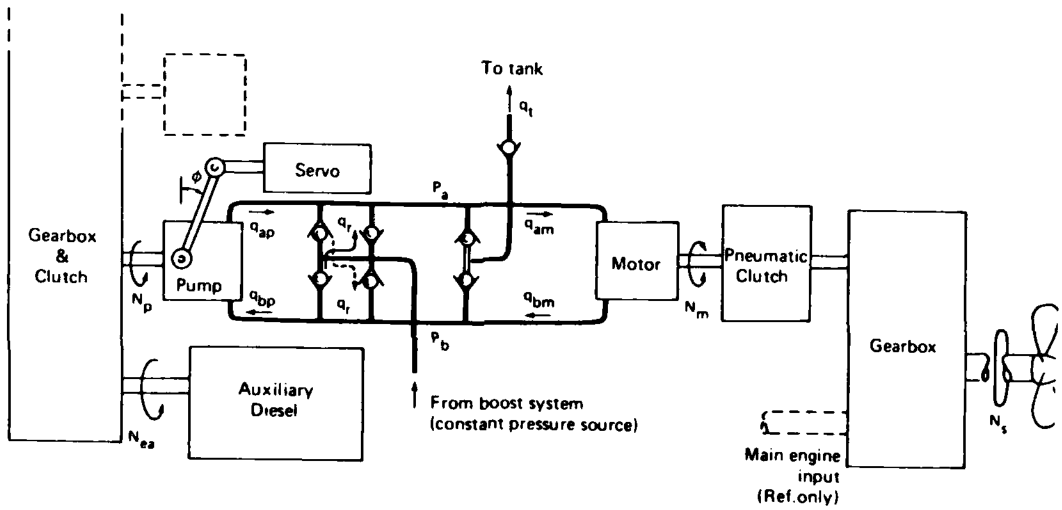
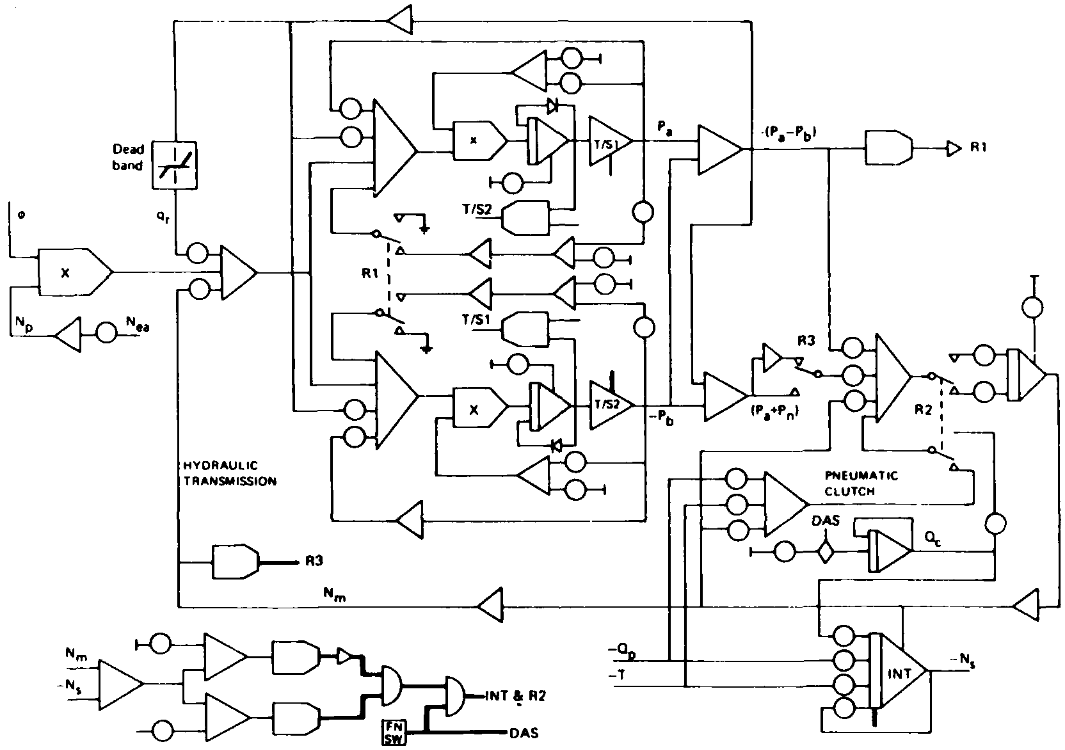

100% Flex Pipe Assumed
20% Flex Pipe
Rated Condition
No Load Condition
Open loop gain - dB
Open loop phase - degrees
36
30
24
18
12
6
0
-6
-12
-18
-210
-180
-150
-120
-90
-60
-30
-1dB
+2dB
+6dB
+12dB
-6dB
-12dB
-210°
-150°
-90°

FIG. 17



SCHEMATIC OF SLOW SPEED DRIVE

FIG. 18(a)



SLOW SPEED DRIVE PATCH DIAGRAM

FIG. 18(b)

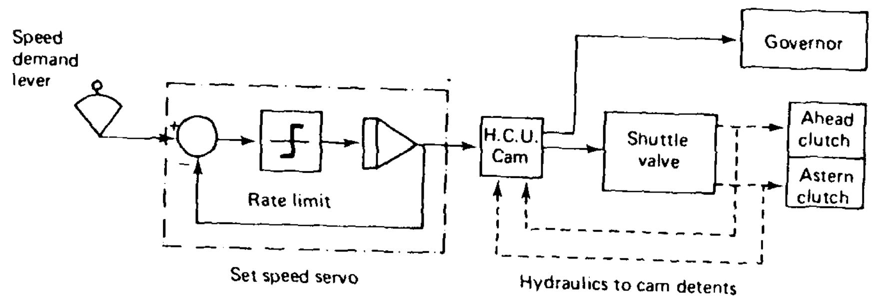


FIG. 20(a)

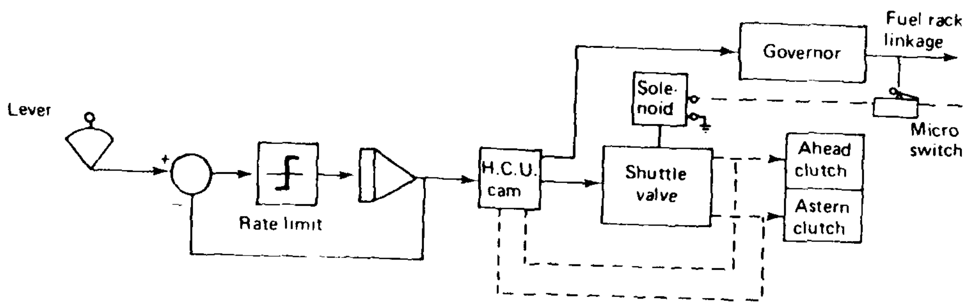


FIG. 20(b)

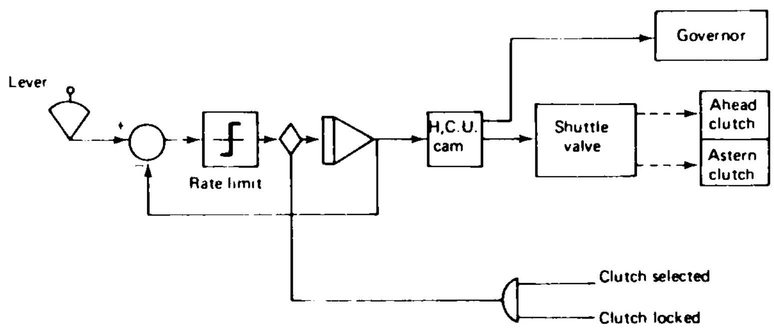

Governor
Lever
+
−
Rate limit
H.C.U.
cam
Shuttle
valve
Ahead
clutch
Astern
clutch
Clutch selected
Clutch locked

FIG. 20(c)

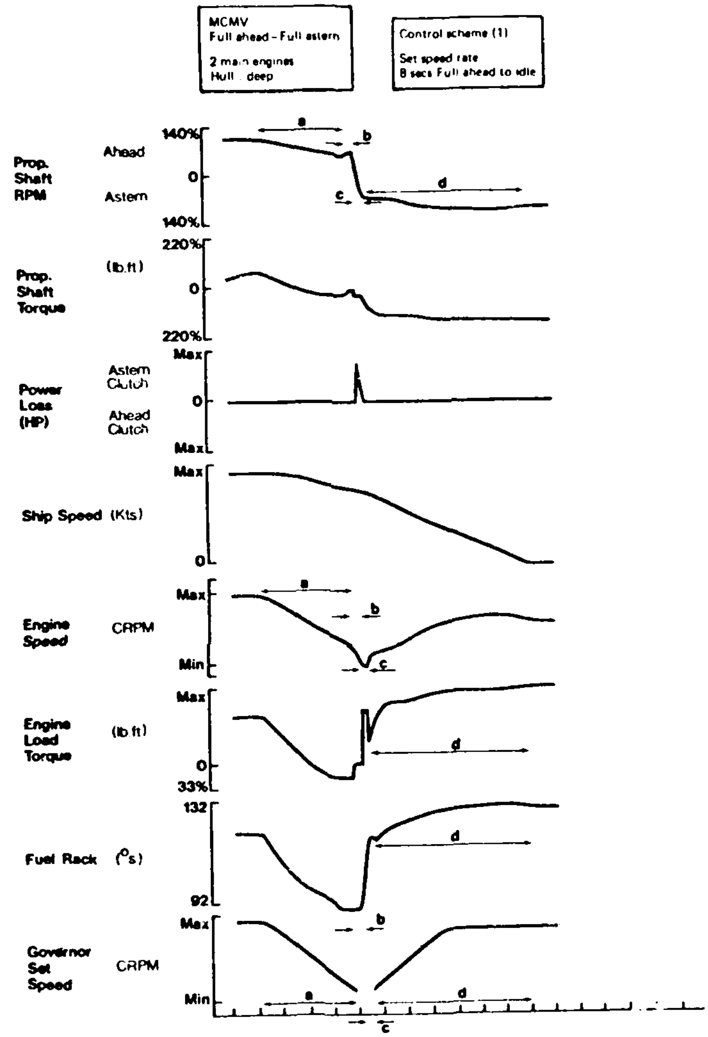
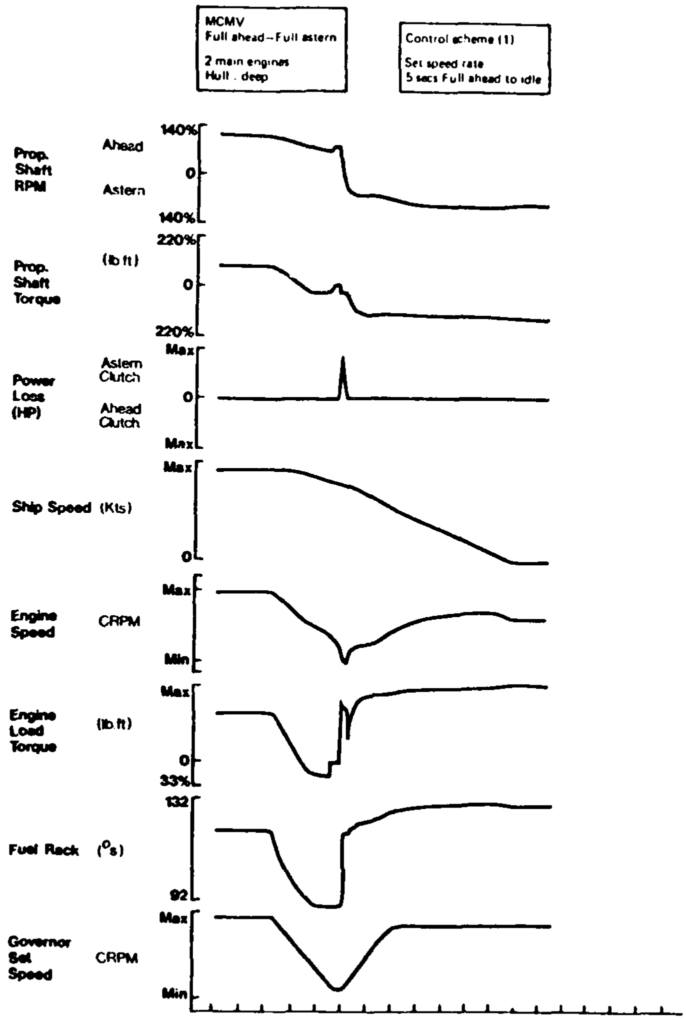

MCMV
Full ahead - Full astern
2 main engines
Hull . deep
Control scheme (1)
Set speed rate
8 secs Full ahead to idle
Prop. Shaft RPM
Ahead
Astern
140%
0
140%
Prop. Shaft Torque
(lb.ft)
220%
0
220%
Power Loss (HP)
Astern Clutch
Ahead Clutch
Max
0
Max
Ship Speed (Kts)
Max
0
Engine Speed
CRPM
Max
Min
Engine Load Torque
(lb.ft)
Max
0
33%
Fuel Rack (°s)
132
92
Governor Set Speed
CRPM
Max
Min
a
b
c
d

FIG. 21



MCMV
Full ahead – Full astern
2 main engines
Hull . deep
Control scheme (1)
Set speed rate
5 secs Full ahead to idle
Prop. Shaft RPM
Ahead
Astern
140%
0
140%
Prop. Shaft Torque
(lb ft)
220%
0
220%
Power Loss (HP)
Astern Clutch
Ahead Clutch
Max
0
Max
Ship Speed (Kts)
Max
0
Engine Speed
CRPM
Max
Min
Engine Load Torque
(lb ft)
Max
0
33%
Fuel Rack
132
92
Governor Set Speed
CRPM
Max
Min

FIG. 22

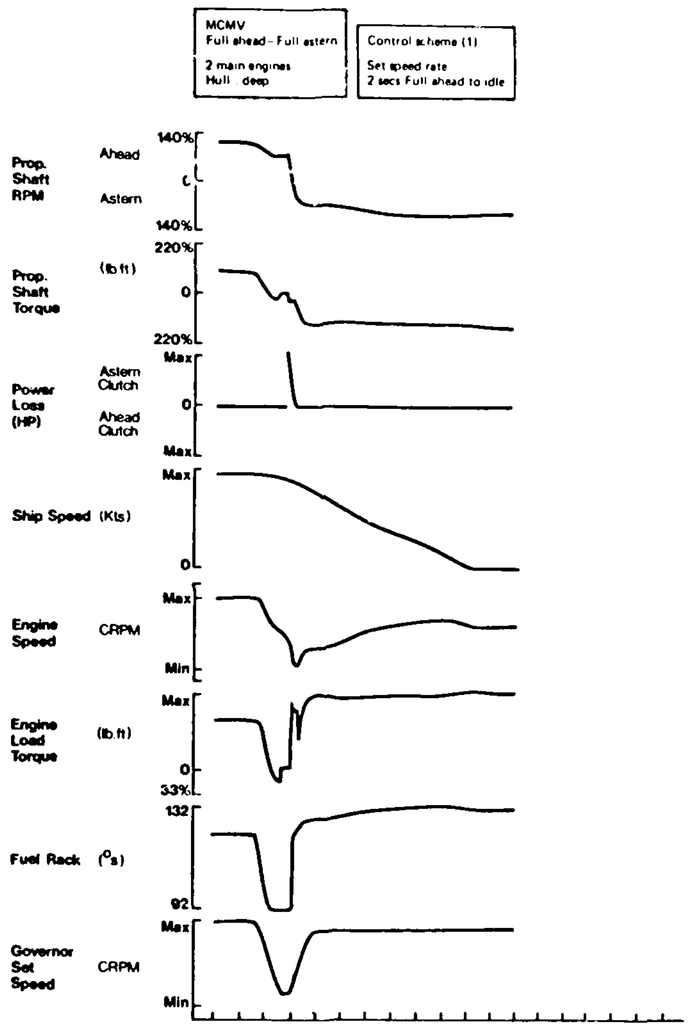
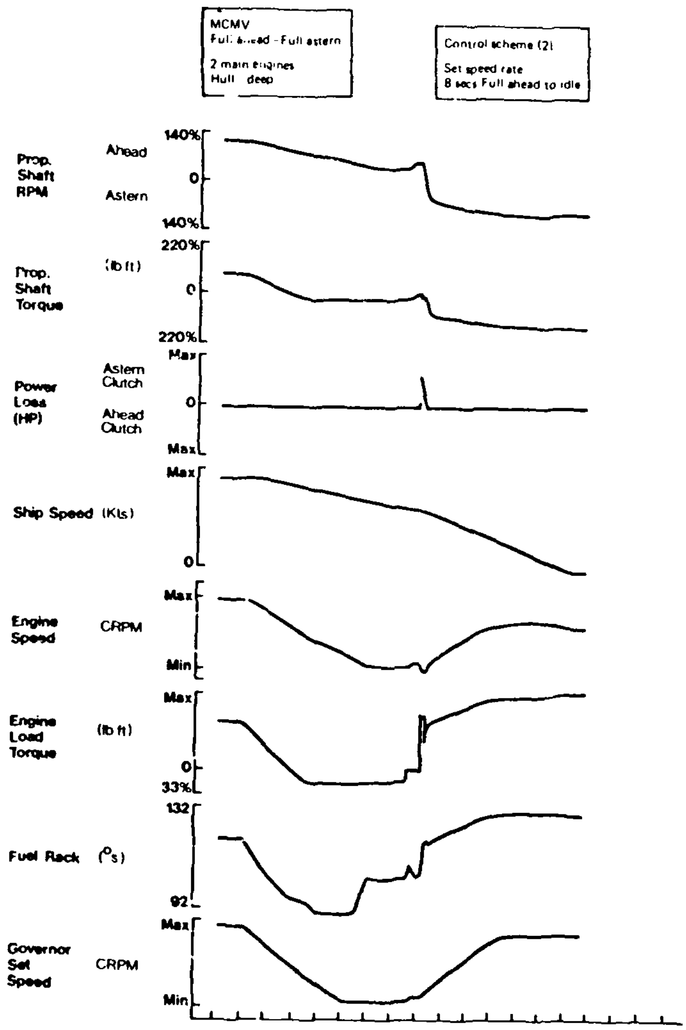

MCMV
Full ahead - Full astern
2 main engines
Hull : deep
Control scheme (1)
Set speed rate
2 secs Full ahead to idle
Prop. Shaft RPM
Ahead
Astern
140%
0
140%
Prop. Shaft Torque
(lb ft)
220%
0
220%
Power Loss (HP)
Astern Clutch
Ahead Clutch
Max
0
Max
Ship Speed (Kts)
Max
0
Engine Speed
CRPM
Max
Min
Engine Load Torque
(lb.ft)
Max
0
33%
Fuel Rack (°s)
132
92
Governor Set Speed
CRPM
Max
Min

FIG. 23



MCMV
Full ahead - Full astern
2 main engines
Hull deep
Control scheme (2)
Set speed rate
8 secs Full ahead to idle
Prop. Shaft RPM
Ahead
Astern
140%
0
140%
220%
Prop. Shaft Torque
(lb ft)
0
220%
Power Loss (HP)
Astern Clutch
Ahead Clutch
Max
0
Max
Ship Speed (Kts)
Max
0
Engine Speed
CRPM
Max
Min
Engine Load Torque
(lb ft)
Max
0
33%
Fuel Rack
(°s)
132
92
Governor Set Speed
CRPM
Max
Min

FIG. 24

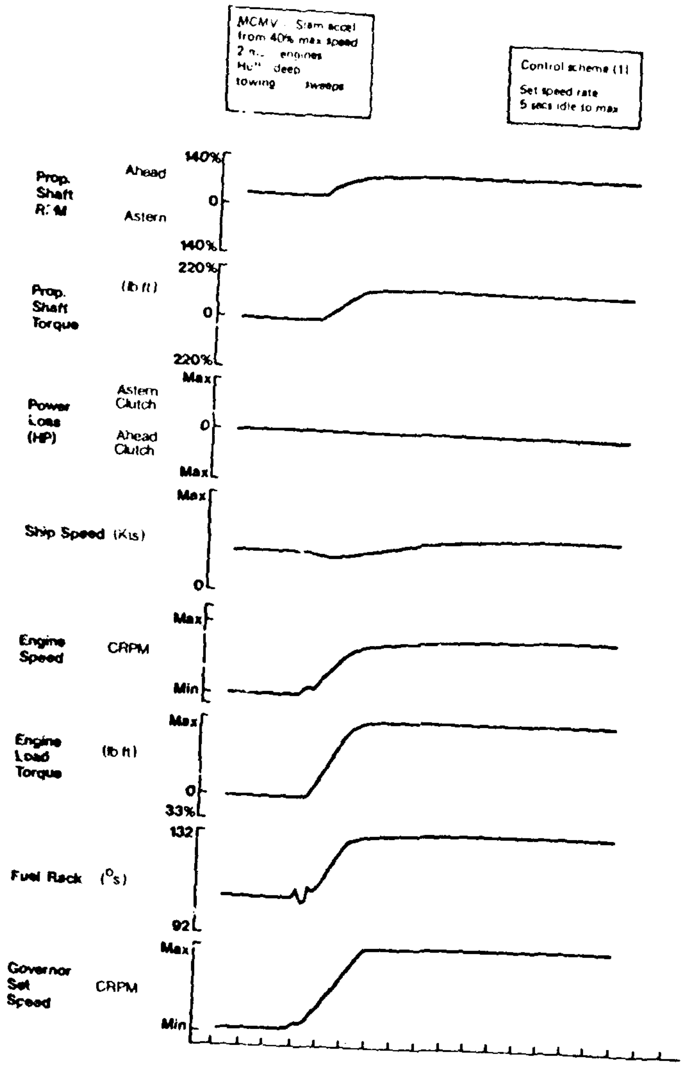

MCMV Slam accel
from 40% max speed
engines
deep
towing sweeps
Control scheme (1)
Set speed rate
5 secs idle to max
Prop. Shaft RPM
Ahead
Astern
140%
0
140%
Prop. Shaft Torque
(lb ft)
220%
0
220%
Power Loss (HP)
Astern Clutch
Ahead Clutch
Max
0
Max
Ship Speed (Kts)
Max
0
Engine Speed
CRPM
Max
Min
Engine Load Torque
(lb ft)
Max
0
33%
Fuel Rack
132
92
Governor Set Speed
CRPM
Max
Min

FIG. 39

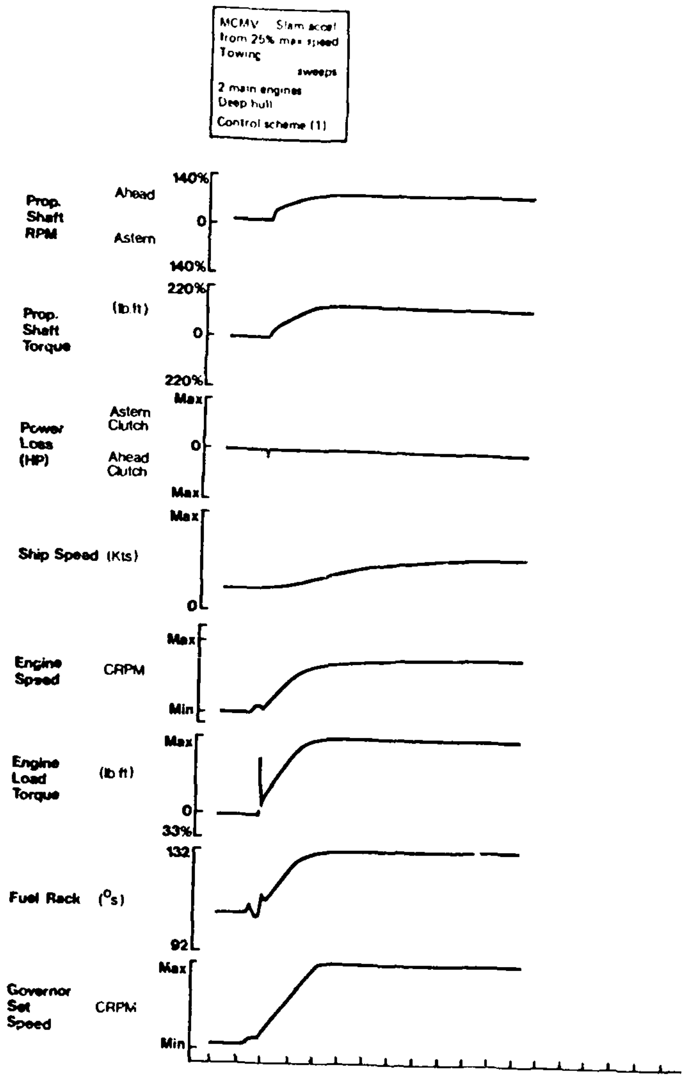

MCMV Slam accel
from 25% max speed
Towing
sweeps
2 main engines
Deep hull
Control scheme (1)
Prop. Shaft RPM
Ahead
Astern
140%
0
140%
Prop. Shaft Torque
(lb ft)
220%
0
220%
Power Loss (HP)
Astern Clutch
Ahead Clutch
Max
0
Max
Ship Speed (Kts)
Max
0
Engine Speed
CRPM
Max
Min
Engine Load Torque
(lb ft)
Max
0
33%
Fuel Rack (°s)
132
92
Governor Set Speed
CRPM
Max
Min

FIG. 38

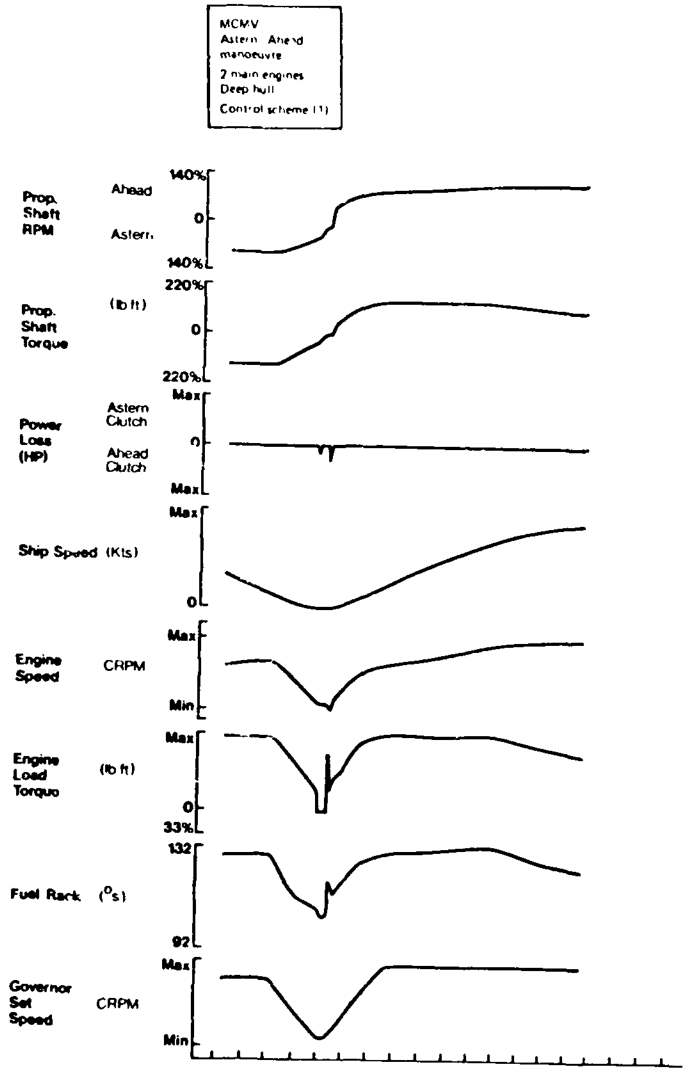

MCMV
Astern Ahead manoeuvre
2 main engines
Deep hull
Control scheme (1)
Prop. Shaft RPM
Ahead
Astern
140%
0
140%
Prop. Shaft Torque
(lb ft)
220%
0
220%
Power Loss (HP)
Astern Clutch
Ahead Clutch
Max
0
Max
Ship Speed (Kts)
Max
0
Engine Speed
CRPM
Max
Min
Engine Load Torque
(lb ft)
Max
0
33%
Fuel Rack
(°s)
132
92
Governor Set Speed
CRPM
Max
Min

FIG. 37

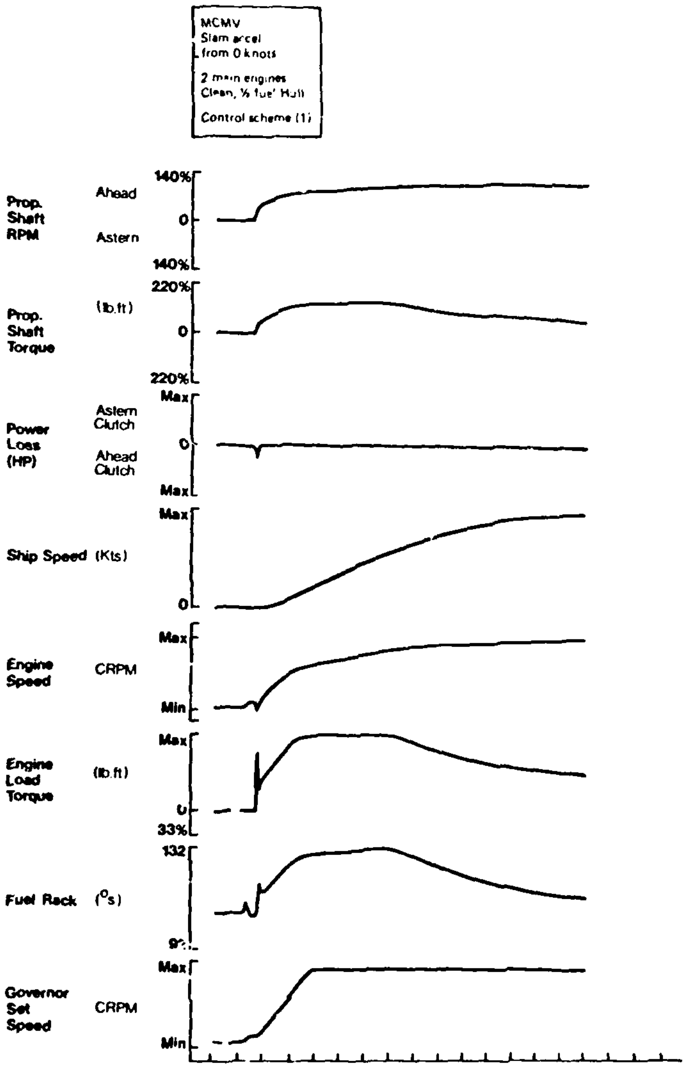

MCMV
Slam accel
from 0 knots
Clean, ½ fuel Hull
Control scheme (1)
Prop. Shaft RPM
Ahead
Astern
140%
0
140%
Prop. Shaft Torque
(lb.ft)
220%
0
220%
Power Loss (HP)
Astern Clutch
Ahead Clutch
Max
0
Max
Ship Speed (Kts)
Max
0
Engine Speed
CRPM
Max
Min
Engine Load Torque
(lb.ft)
Max
0
33%
Fuel Rack
(°s)
132
Governor Set Speed
CRPM
Max
Min

FIG. 36

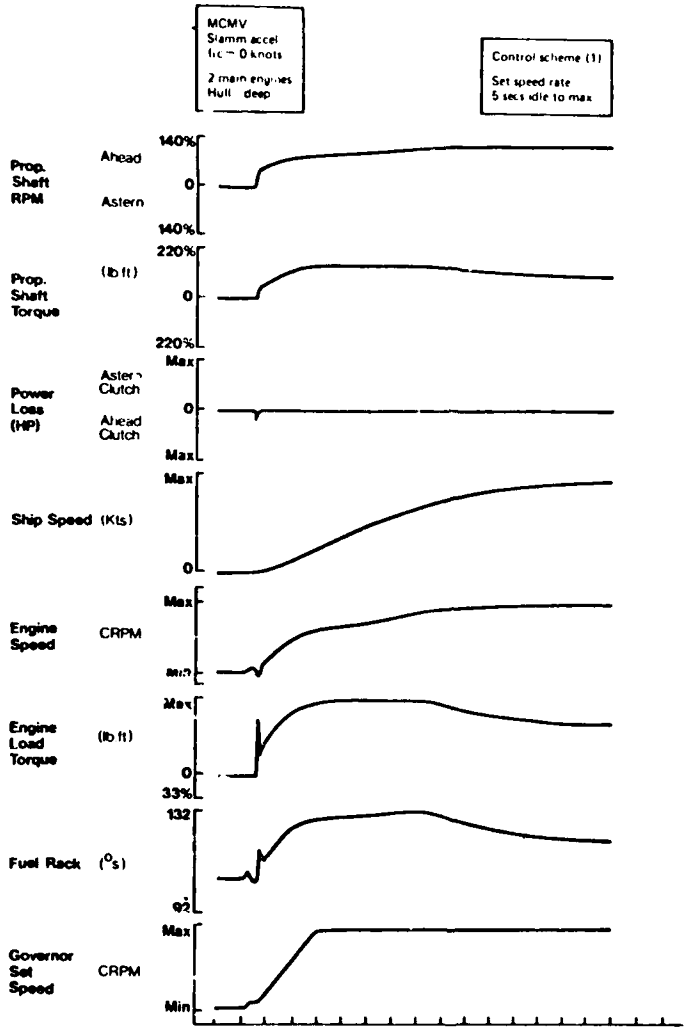

MCMV
Slamm accel
i.c = 0 knots
2 main engines
Hull deep
Control scheme (1)
Set speed rate
5 secs idle to max
Prop. Shaft RPM
Ahead
Astern
140%
0
140%
Prop. Shaft Torque
(lb ft)
220%
0
220%
Power Loss (HP)
Astern Clutch
Ahead Clutch
Max
0
Max
Ship Speed (Kts)
Max
0
Engine Speed
CRPM
Max
Min
Engine Load Torque
(lb ft)
Max
0
33%
Fuel Rack
(°s)
132
92
Governor Set Speed
CRPM
Max
Min

FIG. 35

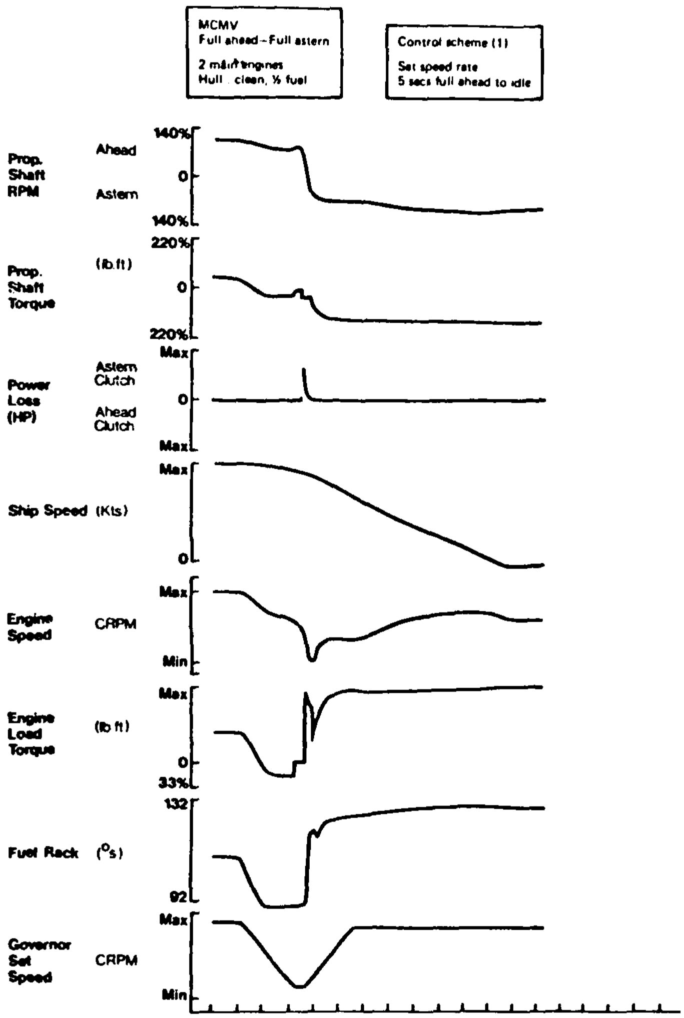
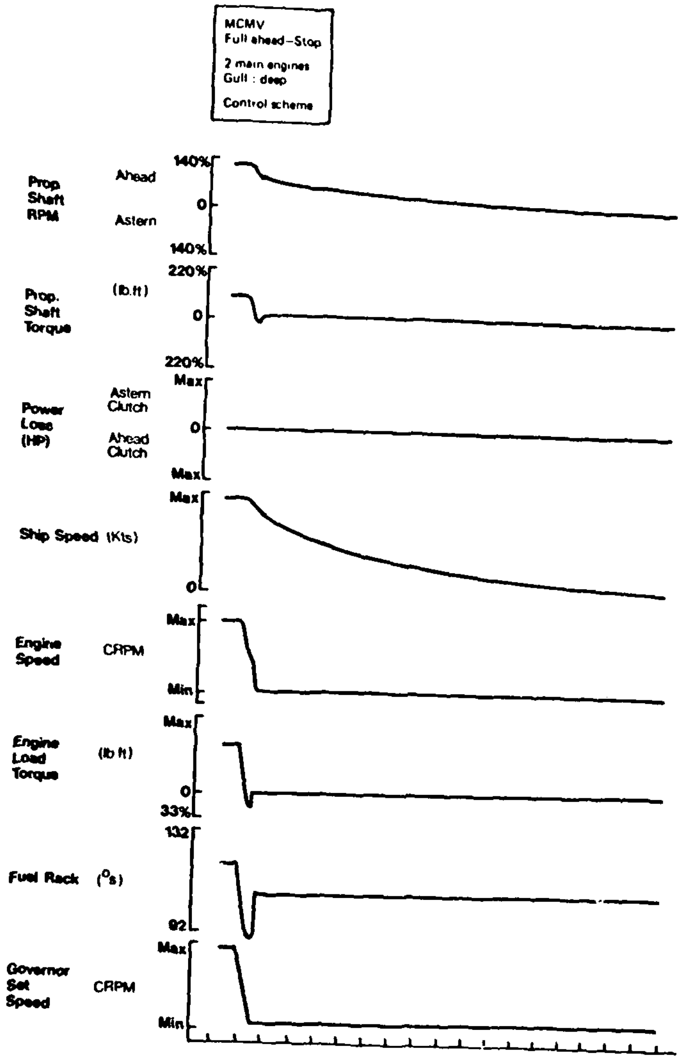

MCMV
Full ahead – Full astern
Hull . clean, ½ fuel
Control scheme (1)
Set speed rate
5 secs full ahead to idle
Prop. Shaft RPM
Ahead
Astern
140%
0
140%
Prop. Shaft Torque
(lb.ft)
220%
0
220%
Power Loss (HP)
Astern Clutch
Ahead Clutch
Max
0
Max
Ship Speed (Kts)
Max
0
Engine Speed
CRPM
Max
Min
Engine Load Torque
(lb ft)
Max
0
33%
Fuel Rack
(°s)
132
92
Governor Set Speed
CRPM
Max
Min

FIG. 34



MCMV
Full ahead–Stop
2 main engines
Gull : deep
Control scheme
Prop Shaft RPM
Ahead
Astern
140%
0
140%
Prop. Shaft Torque
(lb.ft)
220%
0
220%
Power Loss (HP)
Astern Clutch
Ahead Clutch
Max
0
Max
Ship Speed (Kts)
Max
0
Engine Speed
CRPM
Max
Min
Engine Load Torque
(lb ft)
Max
0
33%
Fuel Rack
(°s)
132
92
Governor Set Speed
CRPM
Max
Min

FIG. 33

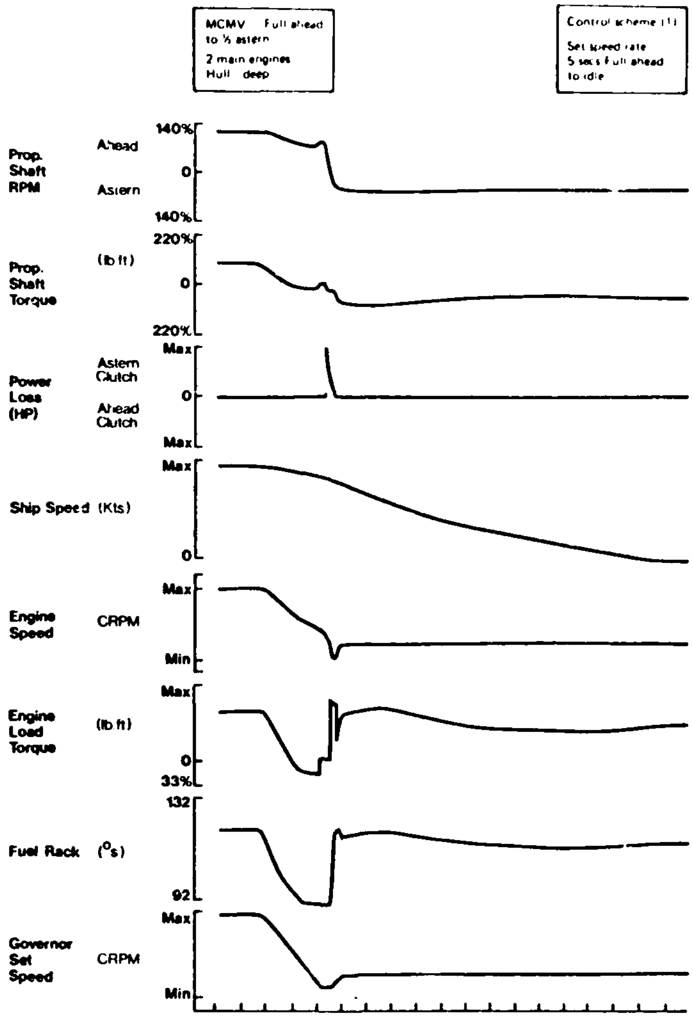

MCMV Full ahead
to ½ astern
2 main engines
Hull deep
Control scheme (1)
Set speed rate
5 secs Full ahead
to idle
Prop. Shaft RPM
Ahead
Astern
140%
0
140%
Prop. Shaft Torque
(lb ft)
220%
0
220%
Power Loss (HP)
Astern Clutch
Ahead Clutch
Max
0
Max
Ship Speed (Kts)
Max
0
Engine Speed
CRPM
Max
Min
Engine Load Torque
(lb ft)
Max
0
33%
Fuel Rack
(°s)
132
92
Governor Set Speed
CRPM
Max
Min

FIG. 32

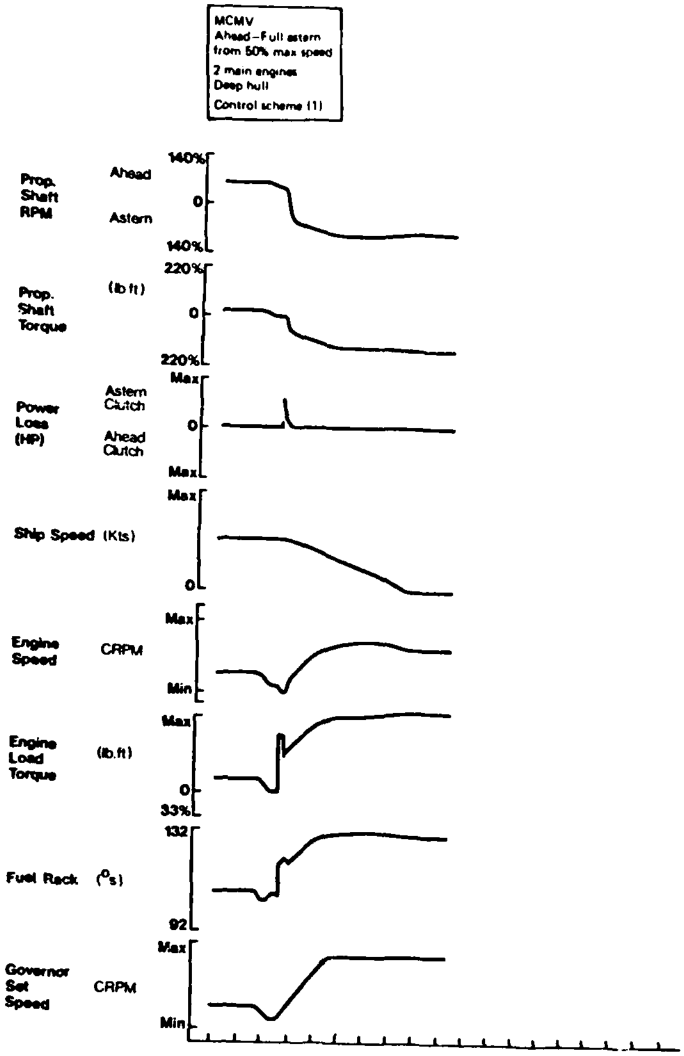

MCMV
Ahead – Full astern
from 50% max speed
2 main engines
Deep hull
Control scheme (1)
Prop. Shaft RPM
Ahead
Astern
140%
0
140%
Prop. Shaft Torque
(lb ft)
220%
0
220%
Power Loss (HP)
Astern Clutch
Ahead Clutch
Max
0
Max
Ship Speed (Kts)
Max
0
Engine Speed
CRPM
Max
Min
Engine Load Torque
(lb.ft)
Max
0
33%
Fuel Rack
(°s)
132
92
Governor Set Speed
CRPM
Max
Min

FIG. 31

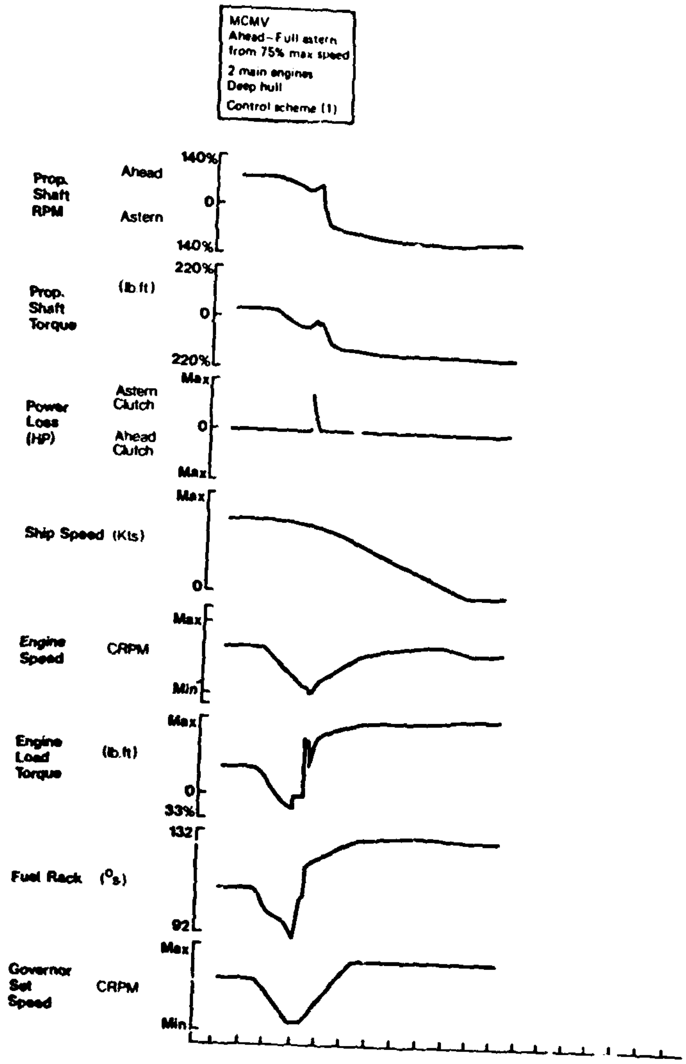
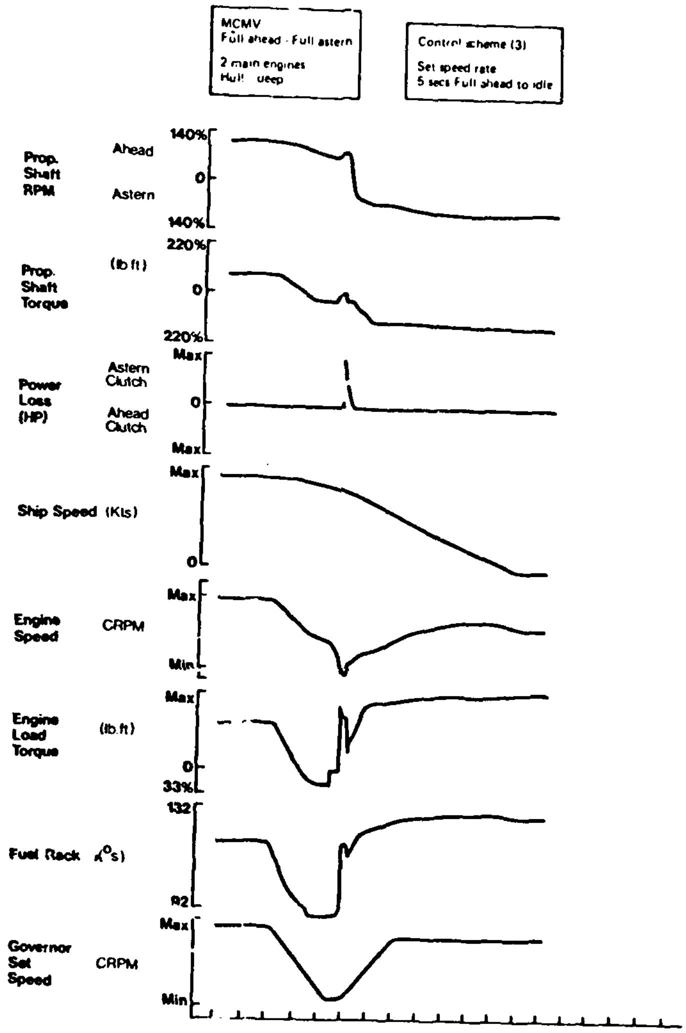

MCMV
Ahead – Full astern
from 75% max speed
2 main engines
Deep hull
Control scheme (1)
Prop. Shaft RPM
Ahead
Astern
140%
0
140%
Prop. Shaft Torque
(lb ft)
220%
0
220%
Power Loss (HP)
Astern Clutch
Ahead Clutch
Max
0
Max
Ship Speed (Kts)
Max
0
Engine Speed
CRPM
Max
Min
Engine Load Torque
(lb.ft)
Max
0
33%
Fuel Rack
132
92
Governor Set Speed
CRPM
Max
Min

FIG. 29



MCMV
Full ahead - Full astern
2 main engines
Hull deep
Control scheme (3)
Set speed rate
5 secs Full ahead to idle
Prop. Shaft RPM
Ahead
Astern
140%
0
140%
Prop. Shaft Torque
(lb ft)
220%
0
220%
Power Loss (HP)
Astern Clutch
Ahead Clutch
Max
0
Max
Ship Speed (Kts)
Max
0
Engine Speed
CRPM
Max
Min
Engine Load Torque
(lb.ft)
Max
0
33%
Fuel Rack
132
Governor Set Speed
CRPM
Max
Min

FIG. 28

FULL AHEAD–FULL ASTERN MANOEUVRE
2 MAIN ENGINES 'DEEP' HULL

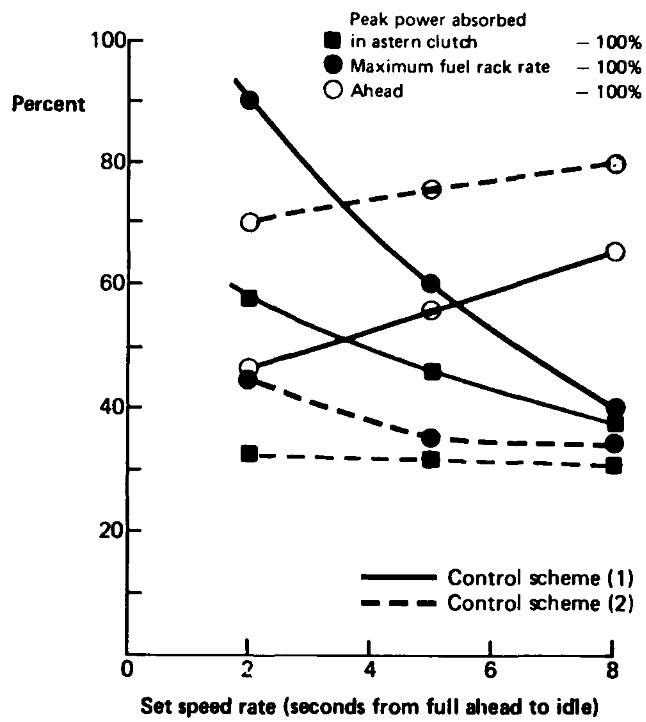


FIG. 27

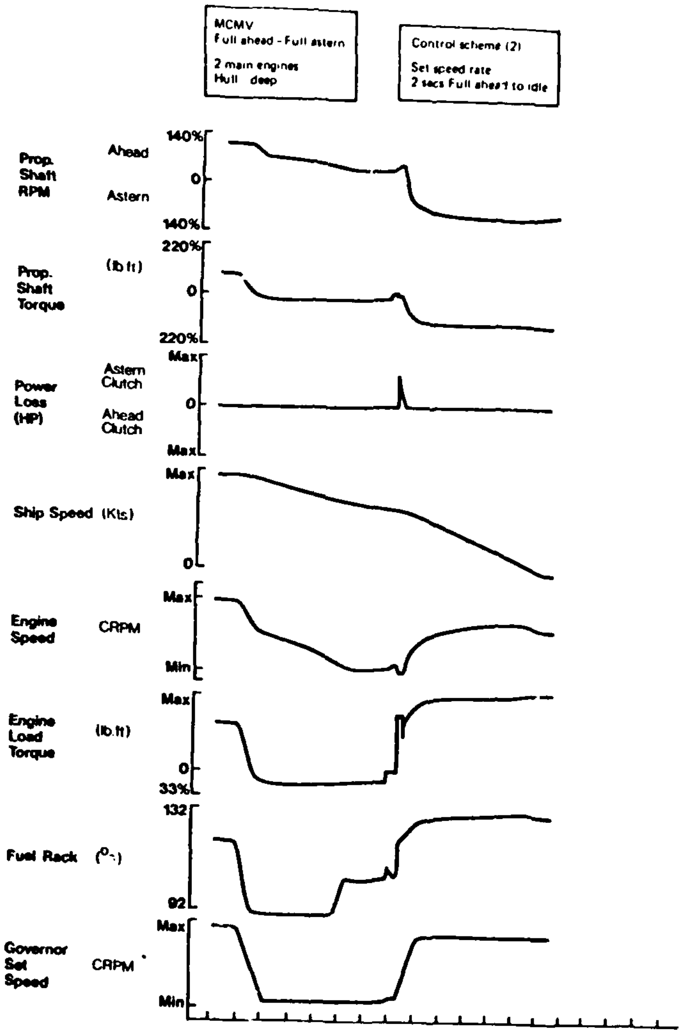

MCMV
Full ahead - Full astern
2 main engines
Hull deep
Control scheme (2)
Set speed rate
2 secs Full ahead to idle
Prop. Shaft RPM
Ahead
Astern
140%
0
140%
Prop. Shaft Torque
(lb ft)
220%
0
220%
Power Loss (HP)
Astern Clutch
Ahead Clutch
Max
0
Max
Ship Speed (Kts)
Max
0
Engine Speed
CRPM
Max
Min
Engine Load Torque
(lb.ft)
Max
0
33%
Fuel Rack
132
92
Governor Set Speed
CRPM
Max
Min

FIG. 26

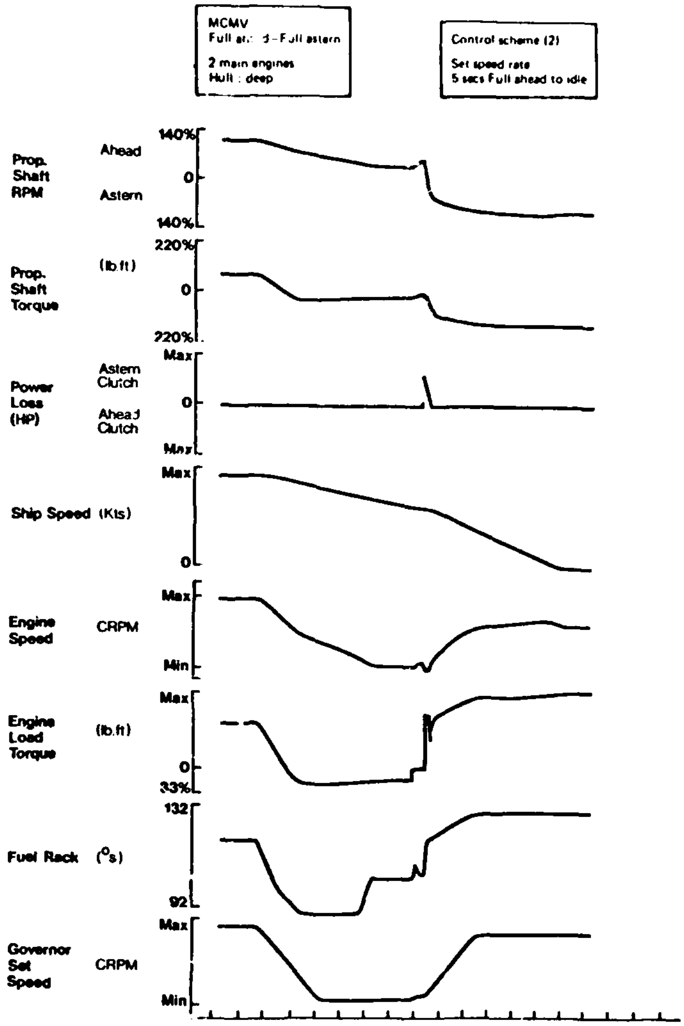
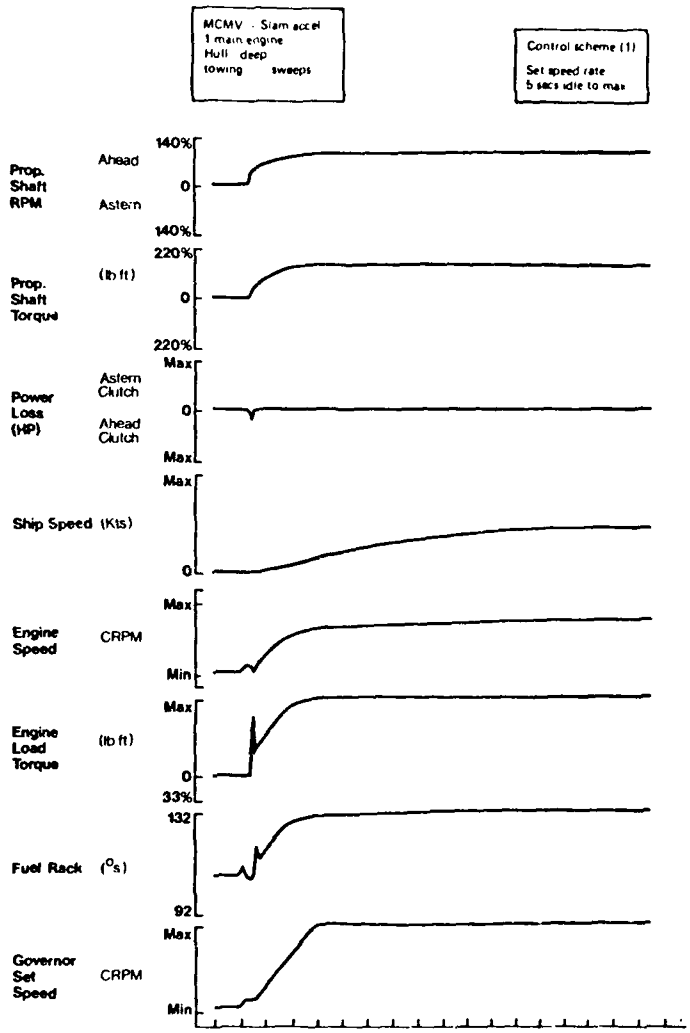

MCMV
Full ahead - Full astern
2 main engines
Hull : deep
Control scheme (2)
Set speed rate
5 secs Full ahead to idle
Prop. Shaft RPM
Ahead
Astern
140%
0
140%
Prop. Shaft Torque
(lb.ft)
220%
0
220%
Power Loss (HP)
Astern Clutch
Ahead Clutch
Max
0
Max
Ship Speed (Kts)
Max
0
Engine Speed
CRPM
Max
Min
Engine Load Torque
(lb.ft)
Max
0
33%
Fuel Rack
(°s)
132
92
Governor Set Speed
CRPM
Max
Min

FIG. 25



MCMV · Slam accel
1 main engine
Hull deep
towing sweeps
Control scheme (1)
Set speed rate
5 secs idle to max
Prop. Shaft RPM
Ahead
Astern
140%
0
140%
Prop. Shaft Torque
(lb ft)
220%
0
220%
Power Loss (HP)
Astern Clutch
Ahead Clutch
Max
0
Max
Ship Speed (Kts)
Max
0
Engine Speed
CRPM
Max
Min
Engine Load Torque
(lb ft)
Max
0
33%
Fuel Rack
(°s)
132
92
Governor Set Speed
CRPM
Max
Min

FIG. 40

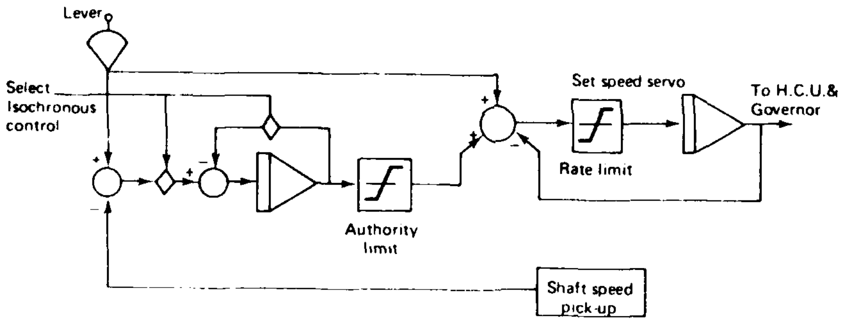

Lever
Select
Isochronous
control
Set speed servo
To H.C.U.&
Governor
Rate limit
Authority
limit
Shaft speed
pick-up

FIG. 41

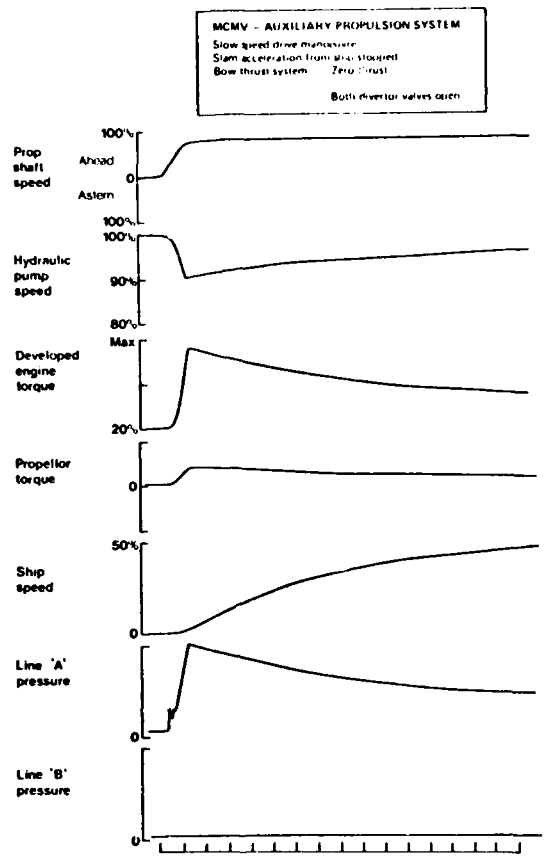
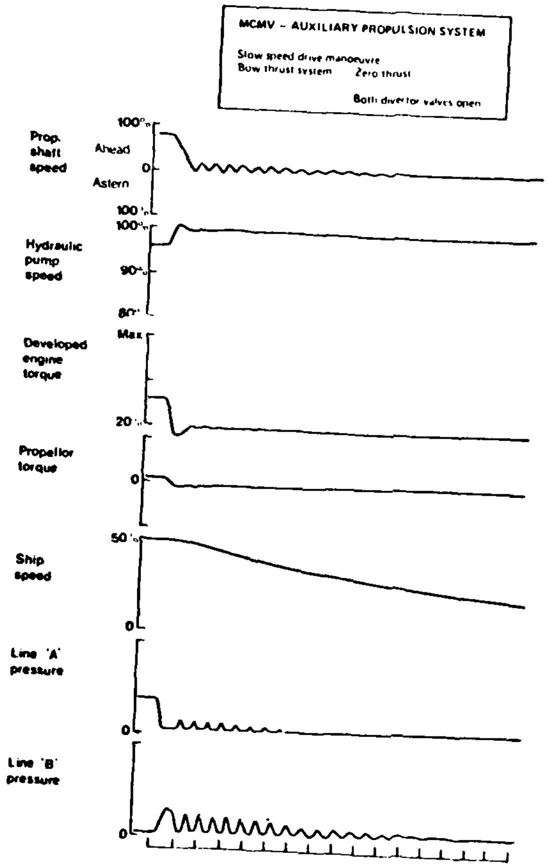

MCMV – AUXILIARY PROPULSION SYSTEM
Slam acceleration
Bow thrust system
Prop shaft speed
Ahead
Astern
100%
0
100%
Hydraulic pump speed
100%
90%
80%
Developed engine torque
Max
20%
Propellor torque
0
Ship speed
50%
0
Line 'A' pressure
0
Line 'B' pressure
0

FIG. 42



MCMV – AUXILIARY PROPULSION SYSTEM
Slow speed drive manoeuvre
Bow thrust system
Zero thrust
Both divertor valves open
Prop. shaft speed
100%
Ahead
0
Astern
100%
Hydraulic pump speed
100%
90%
Developed engine torque
Max
20%
Propellor torque
0
Ship speed
50%
0
Line 'A' pressure
0
Line 'B' pressure
0

FIG. 43

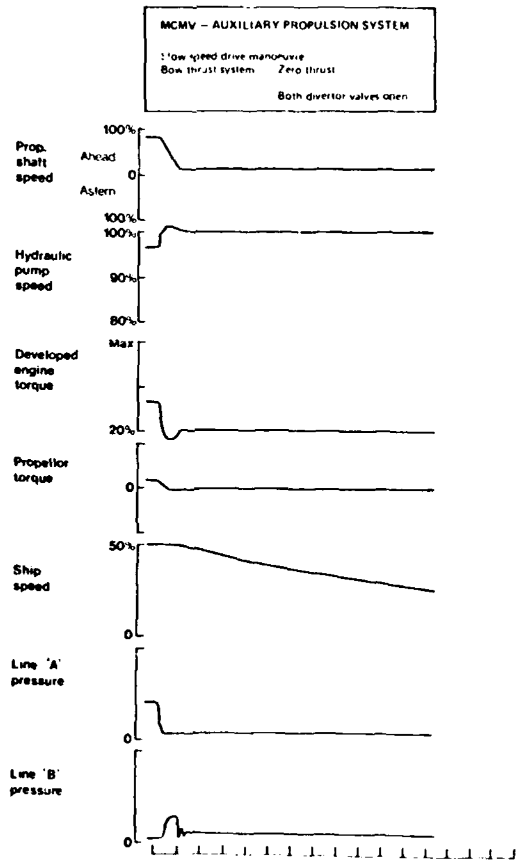
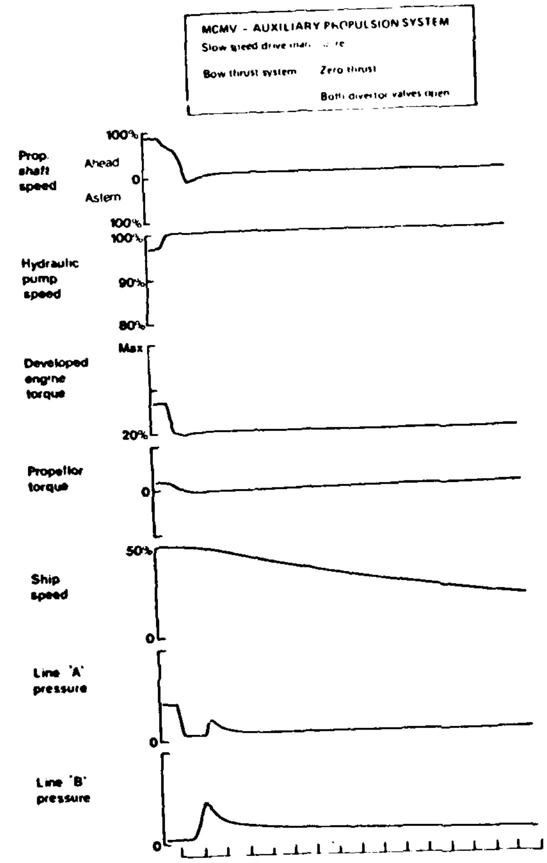

MCMV – AUXILIARY PROPULSION SYSTEM
Bow thrust system
Zero thrust
Both divertor valves open
Prop. shaft speed
100%
Ahead
0
Astern
100%
Hydraulic pump speed
100%
90%
80%
Developed engine torque
Max
20%
Propellor torque
0
Ship speed
50%
0
Line 'A' pressure
0
Line 'B' pressure
0

FIG. 44



MCMV - AUXILIARY PROPULSION SYSTEM
Bow thrust system
Zero thrust
Prop. shaft speed
100%
Ahead
0
Astern
100%
Hydraulic pump speed
100%
90%
80%
Developed engine torque
Max
20%
Propellor torque
0
Ship speed
50%
0
Line 'A' pressure
0
Line 'B' pressure
0

FIG. 45

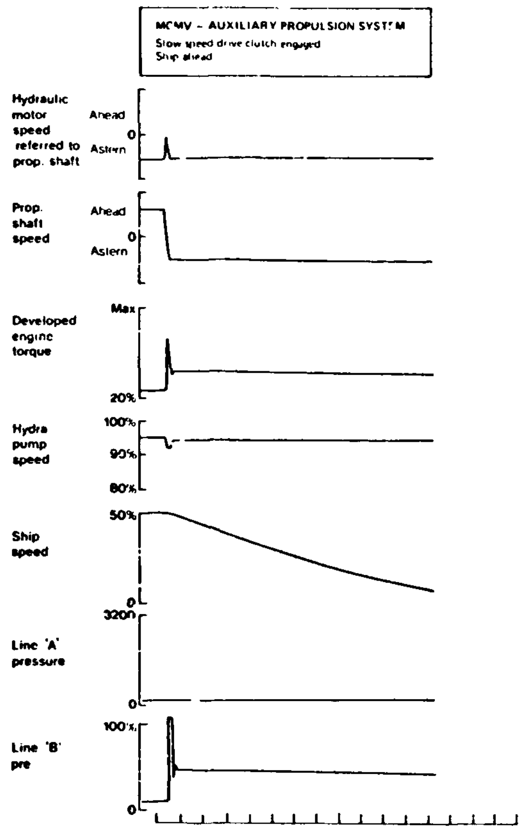

MCMV – AUXILIARY PROPULSION SYSTEM
Slow speed drive clutch engaged
Ship ahead
Hydraulic motor speed referred to prop. shaft
Ahead
0
Astern
Prop. shaft speed
Ahead
0
Astern
Developed engine torque
Max
20%
Hydra pump speed
100%
90%
80%
Ship speed
50%
0
Line 'A' pressure
3200
0
Line 'B' pre
100%
0

FIG. 46

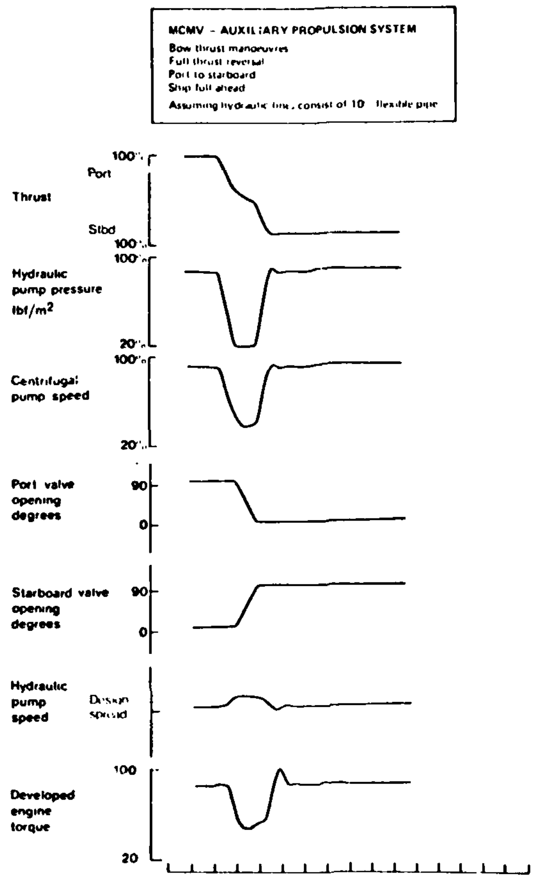

MCMV - AUXILIARY PROPULSION SYSTEM
Bow thrust manoeuvres
Full thrust reversal
Port to starboard
Ship full ahead
Assuming hydraulic line, consist of 10 flexible pipe
100%
Port
Thrust
Stbd
100%
100%
Hydraulic
pump pressure
lbf/m2
20%
100%
Centrifugal
pump speed
20%
Port valve
opening
degrees
90
0
Starboard valve
opening
degrees
90
0
Hydraulic
pump
speed
Design
speed
100
Developed
engine
torque
20

FIG. 47

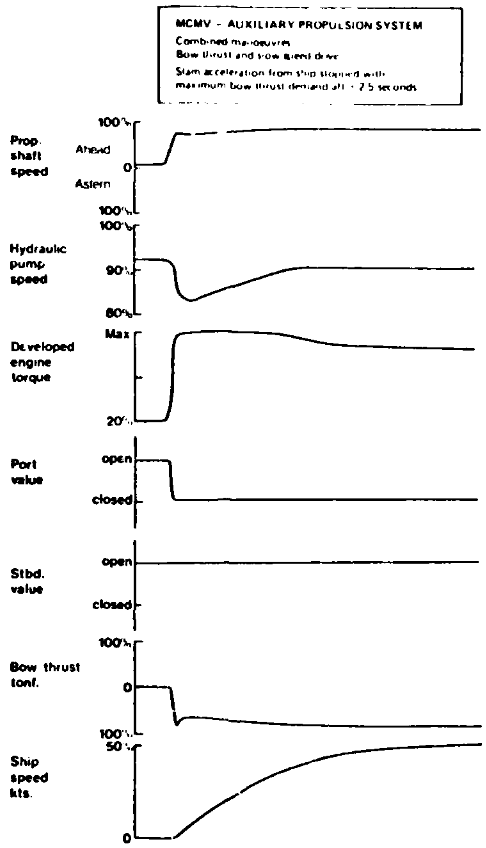

MCMV - AUXILIARY PROPULSION SYSTEM
Combined manoeuvres
Prop. shaft speed
100%
Ahead
0
Astern
100%
Hydraulic pump speed
100%
90%
80%
Developed engine torque
Max
20%
Port value
open
closed
Stbd. value
open
closed
Bow thrust tonf.
100%
0
100%
Ship speed kts.
50%
0

FIG. 48

PROPULSION CONTROL OPTIMIZATION OF CRP PROPELLER DRIVEN SHIPS

J. W. Donnelly
Naval Ship Engineering Center, Philadelphia Division, Philadelphia, PA 19112

ABSTRACT

An optimal propulsion control algorithm for emergency "braking" of a controllable reversible pitch (CRP) propeller driven ship is identified and then applied to a computer simulation of a specific ship. The algorithm fully exploits the inherent ship performance enhancement potential of the CRP propeller to effect minimization of ship reach in a crash-back maneuver. The dynamic responses of all of the relevant ship powering system parameters are presented for the maneuver: Full Ahead to Crash Astern for various values of pitch stroke rate and astern thrust bearing load limit. Under optimal control, ship reach is shown to depend primarily upon the astern thrust bearing load limit.

INTRODUCTION

The CRP propeller has been successfully combined with steam generators and diesel plants and more recently with gas turbines in the Navy's two newest major gas turbine combatants, the DD-963 and FFG-7. Not only does it obviate the need for a separate astern turbine in steam based propulsion systems and reversing gears and clutches in diesel and gas turbine powered ships, but the CRP propeller also provides especially "fine" ship speed control at low ship speeds, and enhances overall ship maneuverability as well. The ship performance improvement potential of CRP propellers is widely recognized, but existing propulsion control systems are based on algorithms that fail to fully exploit that potential, particularly during emergency ship braking maneuvers. This may be a result in part of the relatively modest maneuvering requirements that were imposed on CRP propeller driven ships. "Trial" data obtained on ships for conventional propulsion systems were used to derive the performance requirements with ships that feature the more responsive CRP propeller based systems so that satisfactory braking was demonstrated even under dynamically conservative control. The algorithm presented in this paper is optimal for braking maneuvers since it is the solution to the problem of determining the control methodology that minimizes ship reach.

The optimal control algorithm was applied to a computer simulation of the USS PATTERSON (DE-1061), a steam powered ship. (The decision to select this particular vessel was based on the need for a full complement of maneuvering data on a CRP propeller driven ship in order to validate the ship simulation. At the time that this study was undertaken, such data were unavailable for all but this particular ship[1]). The fact that the propulsion system is steam based in no way compromises the generality of the algorithm. The results derived from its application to the simulation of this ship are, at least from a qualitative standpoint, typical of the performance to be expected with the algorithm applied to a gas turbine powered vessel. Indeed, the algorithm is actually better suited to ships possessing high performance propulsion systems, such as those in the DD-963 and FFG-7 class ships.

NOMENCLATURE

D_p	propeller diameter	ft
D_S	ship reach	yards
F_a	thrust	lb
$\bar{F}_a$	open-water thrust	lb
$\hat{F}_a$	astern bearing load limit	lb
ΔF	net ship accelerating force	lb
J	advance coefficient	rev^{-1}
J_p	drive train inertia	lb ft sec^2
K_p	propeller pitch ratio rate	sec^{-1}
K_Q	propeller torque coefficient	rev^{-2}
K_T	propeller thrust coefficient	rev^{-2}
K_{TT}	steam throttle valve stroke rate	turns sec^{-1}
M_S	ship weight	long tons
N_p	propeller speed	rpm
$\hat{N}_p$	overspeed threshold	rpm
PR	propeller pitch ratio	-
PR_D	propeller pitch ratio setpoint	-
Q_a	engine torque (referred to propeller)	lb ft
Q_f	frictional torque	lb ft
Q_p	propeller load	lb ft
$\hat{Q}_p$	overtorque threshold	lb ft
ΔQ	net shaft accelerating torque	lb ft
R_f	ship resistance	lb
t	time	sec
t_c	thrust deduction fraction	-
t_p	thrust pitch fraction	-
TT	throttle valve position	turns
TT_D	throttle valve position setpoint	turns
ΔT	time interval	sec

V_a	propeller speed of advance	ft sec^{-1}
V_s	ship speed	knots
W_s	steam flow rate	$lb\text{-}hr^{-1}$
β	$Fa/\bar{F}a$	-

SHIP POWERING SYSTEM

Ship stopping distance is a measure of the effectiveness of the propulsion control algorithm in a crash-back maneuver. This distance, D_s, is equal to the time integral of ship speed, V_s over the interval, $(0,t_o)$, "covering" the period between the initiation (t_o) of the maneuver and the achievement of zero ship speed $(V_s(t_o) = 0)$.

$$D_S = .563 \int_0^{t_o} V_s(t)\, dt \qquad \text{yards} \qquad (1)$$

The problem of determining that distance reduces to one of expressing the integrand, $V_s(t)$ in equation (1) as an explicit function of time so that the indicated integration can be performed. That is, V_s must be linked to "known" time dependent system variables.

The differential equation governing ship speed is coupled to the corresponding equation for propeller speed, N_p so that simultaneous solution of both equations is required to obtain the "history" of either variable. For this reason, those two equations are to be regarded as a system.

$$\begin{aligned} \dot{V}_s &= 8.50 \times 10^{-3}\ \Delta F/M_s && \text{knots sec}^{-1} \\ \dot{N}_p &= 9.55\ \Delta Q/J_p && \text{rpm sec}^{-1} \end{aligned} \qquad (2)$$

Equations (2) state that accelerations, $\dot{V}_s$ and $\dot{N}_p$ vary directly with the net force, ΔF and net torque, ΔQ that cause those accelerations and inversely with the related translational (M_s) and rotational (J_p) inertias. ΔF and ΔQ can be replaced by the individual forces and torques that combine to form those resultants. The component torques comprising ΔQ consist of the total engine torque, Q_a, the propeller torque, Q_p, and the frictional torque, Q_f (all referred to the propeller shaft). Similarly, the basic components of ΔF are the effective propeller thrust, F_a and the hull resistance, R_f.

$$\begin{aligned} \Delta Q &= Q_a - Q_p - Q_f && \text{lb ft} \\ \Delta F &= F_a - R_f && \end{aligned} \qquad (3)$$

The functions: R_f and Q_f in equations (3) depend exclusively upon V_s and N_p, respectively.

$$\begin{aligned} R_f &= R_f\ (V_s) && \text{lb} \\ Q_f &= Q_f(N_p) && \text{lb ft} \end{aligned} \qquad (4)$$

In contrast, the functions: Q_a, Q_p, and F_a each depend upon at least two variables.

The steady-state torque developed by each of the twin main propulsion engines is related to the turbine steam flow rate, W_s and speed, N_e. Since both engines are assumed to share the propeller load through a fixed reduction gear box, the total prime mover torque can be summarized by the following equation.

$$Q_a = Q_a(N_p, W_s) \quad \text{lb ft} \qquad (5)$$

"Open water" model propeller data[2] characterize the dependence of propeller torque and thrust on propeller pitch ratio, PR and speed of advance, J. These data prescribe the appropriate values of the torque coefficients, K_Q and thrust coefficients, K_T over the full steady-state ranges of PR and J.

$$\begin{aligned} K_Q &= K_Q\ (PR,\ J) \quad \text{rev}^{-2} \\ K_T &= K_T\ (PR,\ J) \quad \text{rev}^{-2} \end{aligned} \qquad (6)$$

The hybrid variables, PR and J are related to the parameters from which they were synthesized.

$$\begin{aligned} PR &= P/D_p \\ J &= 60\ V_a/N_p\ D_p \quad \text{rev}^{-1} \end{aligned} \qquad (7)$$

(The quantities: P, D_p, and V_a in equations (7) are respectively the propeller, pitch, diameter, and speed of advance). The propeller torque and open water thrust vary directly with their respective model coefficients and nonlinearly with propeller speed and diameter.

$$\begin{aligned} Q_p &= 5.38 \times 10^{-4}\ D_p^{\ 5}\ N_p^{\ 2}\ K_Q \quad \text{lb ft} \\ \bar{F}_a &= 5.38 \times 10^{-4}\ D_p^{\ 4}\ N_p^{\ 2}\ K_T \quad \text{lb} \end{aligned} \qquad (8)$$

The discussion of the mathematical description of the propeller ".....has related to a propeller working in "open water", in which condition it is advancing into undisturbed water. When it is in its correct location behind the model or ship hull, the conditions are considerably modified. The propeller is now working in water which has been disturbed by the passage of the hull, and in general the water around the stern has acquired a forward motion in the same direction as the ship. This forward-moving water is called the wake, and one of the results is that the propeller is no longer advancing relatively to the water at the same speed as the ship, V_s; but at some lower speed, V_a, called the speed of advance."[3] Moreover, ".....the propeller when developing thrust accelerates the water ahead of it, and this has the effect of lowering the pressure around the stern and also increasing the velocity there, both of which effects augment the resistance of the ship above that measured by towing the hull."[3] The data required to characterize these phenomena were unavailable. Accordingly, it was assumed that the propeller speed of advance and the effective thrust varied linearly with ship speed and the open water thrust, respectively.

$$\begin{aligned} V_a &= 1.6\ V_s \quad \text{ft sec}^{-1} \\ F_a &= \beta\ \bar{F}_a \quad \text{lb} \end{aligned} \qquad (9)$$

For a CRP propeller, β is a function of the pitch ratio[2]. Let,

$$\beta = (1 - t_c t_p) \qquad (10)$$

where t_c is a constant and t_p[2] depends upon the propeller pitch ratio.

$$t_p = \begin{cases} 3 & PR \le -1.0 \\ -3\,PR & -1.0 < PR \le 0.0 \\ PR & 0.0 < PR < 1.0 \\ 1 & PR > 1.0 \end{cases} \qquad (11)$$

Equations (3) through (11) implicitely link ΔF and ΔQ to V_s, N_p, PR, and W_s. Since V_s and N_p are the dependent variables in equations (2), that simultaneous pair can be solved if the time dependencies of W_s and PR are known. Both PR and W_s are responses to "known" control system excitations so that V_s and ultimately D_s can be determined when the mathematical links between those responses and their corresponding excitations are established.

Steam flow rate depends entirely upon turbine throttle valve position which in turn can be characterized by the number of throttle turns, TT.

$$W_s = W_s(TT) \qquad \text{lb hr}^{-1} \qquad (12)$$

The value of TT is in turn a consequence of its setpoint. In this study, a fixed valve stroke rate was assumed so that the demanded throttle turns, TT_D is related to TT as follows.

$$\dot{TT} = K_{TT}\ \text{SGN}\ (TT_D - TT) \qquad \text{turns sec}^{-1} \qquad (13)$$

A similar relationship was assumed for PR and its setpoint, PR_D.

$$\dot{PR} = K_p\ \text{SGN}\ (PR_D - PR) \qquad \text{sec}^{-1} \qquad (14)$$

OPTIMAL PROPULSION CONTROL ALGORITHM

The optimization problem posed here is concerned with the identification of a propulsion control algorithm that minimizes the reach of CRP propeller driven ships in a crash-back maneuver. The problem is reducible to one of determining a specialized pair of time trajectories, one for each of the two independent control variables, propeller pitch and throttle valve position. This optimal pair of system inputs provides for the earliest possible application of the maximum achievable or permissible astern thrust without an attendant violation of any of the several basic machinery constraints. Thus, ship reach is to be minimized by maximizing astern thrust subject to the constraints that astern thrust bearing load, turbine speed, and pinion torque never exceed their respective transient design limits.

Ideally, the thrust, $\bar{F}_a$ should be controlled so that it equals the astern thrust bearing load limit, $\hat{F}_a$ for arbitrary values of N_p and V_s.

$$\hat{F}_a = \bar{F}_a\ (PR_D, N_p, V_s) \qquad \text{lb} \qquad (15)$$

The actual pitch ratio, PR differs from its optimal value and cannot be altered to that value instantaneously. Pitch ratio is constrained to obey equation (14) so that at best it can only be "indexed" by an amount $K_p\ \Delta T$ toward PR_D in the interval, ΔT. If t is the "present" time, then the current value of pitch ratio, PR(t) is

SYSTEM DESIGN

System Functional Partitioning

The design of the stabilizer fin control system is partitioned so as to allow remote control and monitoring of the hydraulic system used to position the fins. The control system allows stabilizer operation control and monitoring from two Local Control Units (LCU) located adjacent to the port and starboard hydraulics systems from a Central Control Unit (CCU), normally located in the ship's central control station and from a Bridge Control Unit (BCU) located on the ship's bridge. Digital processing is accomplished within the Central Processing Unit (CPU) which is located in the ship's central control station. An Auxilliary Sensor Unit (ASU), which contains a linear accelerometer and a rate gyro for providing backup ship's positional data in the event that the ship's gyrocompass is not operational, is also located in the central control station. A functional block diagram with each block representing a separate electronics equipment enclosure is shown below as Figure 1.

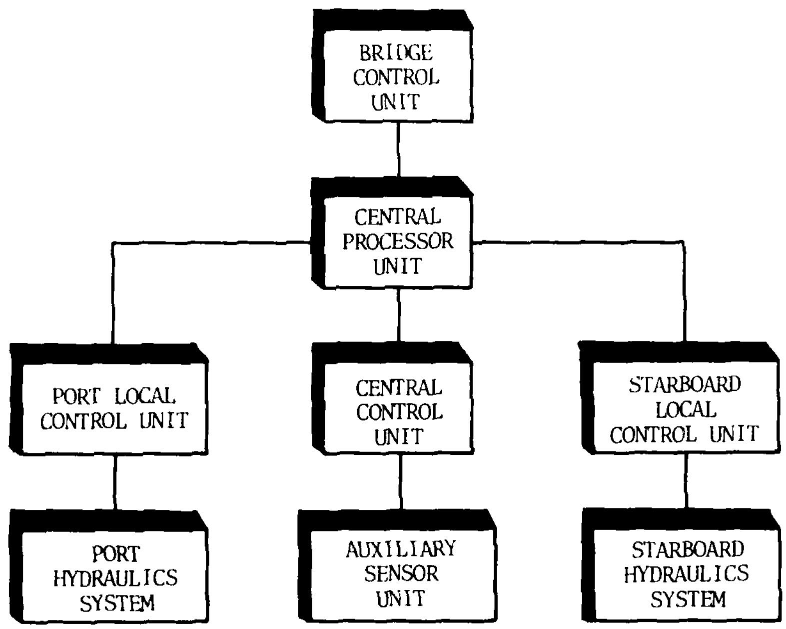


Figure 1. System Block Diagram

A MICROPROCESSOR BASED STABILIZER FIN CONTROL SYSTEM

by James C. Wolford
Module Applications Branch
Naval Weapons Support Center
Crane, Indiana

ABSTRACT

The Navy's Standard Electronic Modules (SEM) Program is a successful modular function standardization program that has been applied to the design, production, and support of electronic systems used on surface ships, submarines, aircraft and missiles. This paper presents the design details of a prototype surface ship control system recently designed, implemented using SEM and tested at sea by Naval Weapons Support Center, Crane.

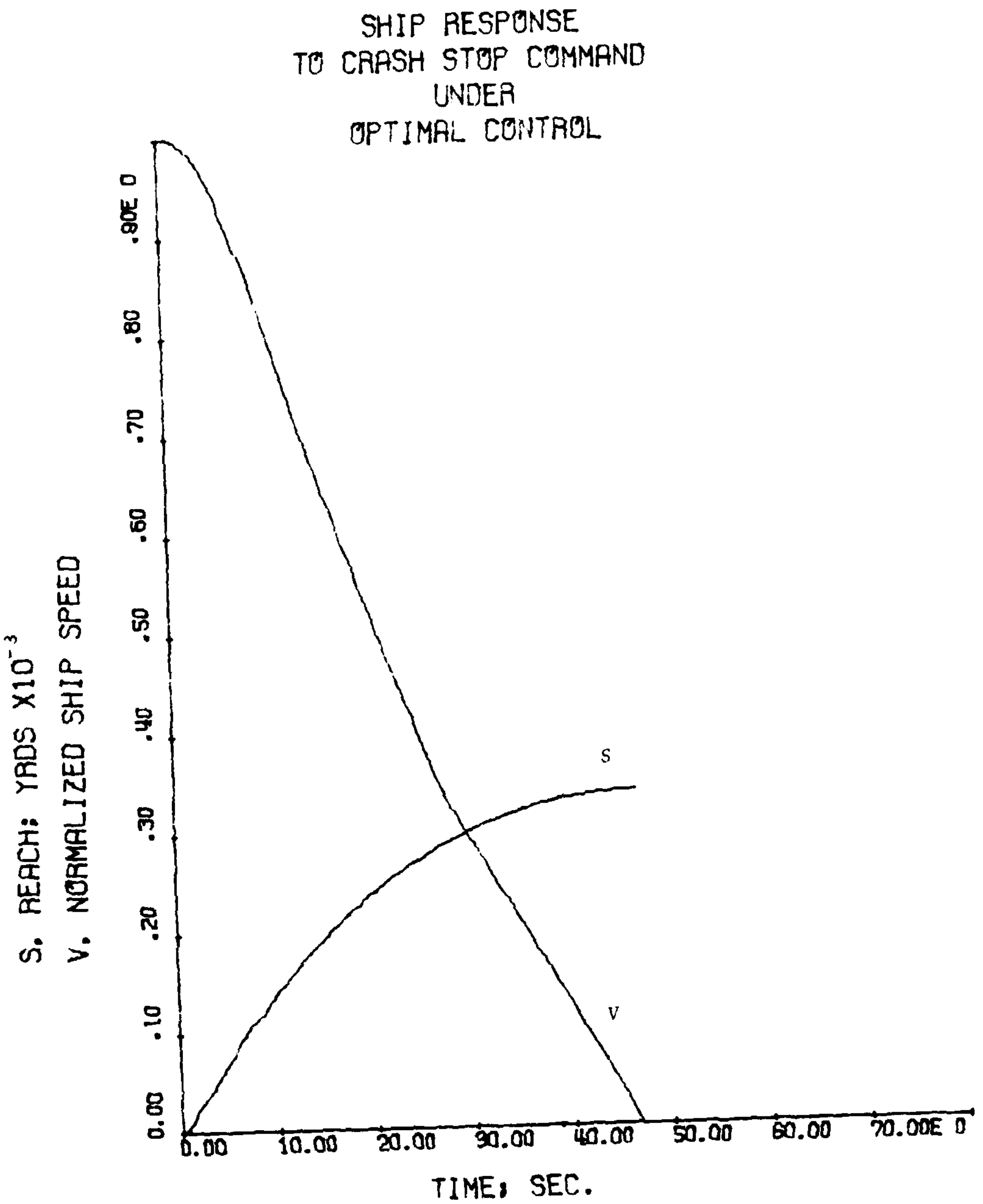
The Stabilizer Fin Control System is a microprocessor-based digital system which accepts ship's roll data from the ship's gyrocompass and from an auxilliary sensor unit, ship's speed from the electromagnetic log, and operator commands from control panels located on the bridge and in the engineering operating space. The system computes fin positional commands to minimize ship's rolling using a second order differential control equation, controls hydraulic pump motors, and performs several digital processing functions including display multiplexing, digital filtering, adaptive gains, compensations for ship's speed and list angle, and system status monitoring and self-tests.

INTRODUCTION

A prototype digital stabilizer fin control system was designed, fabricated and tested at sea by the Naval Weapons Support Center, Crane, Indiana. This project was performed under the direction of Code 6165, Naval Ships Engineering Center, Washington, D.C. in conjunction with a stabilizer hydraulics improvement program which was accomplished in parallel by Naval Ships Engineering Center, Philadelphia, Pennsylvania. Shipboard installation and sea trial testing of the control system were accomplished during the period from June 1977 to March 1978 aboard the USS Glover (AGFF-1).

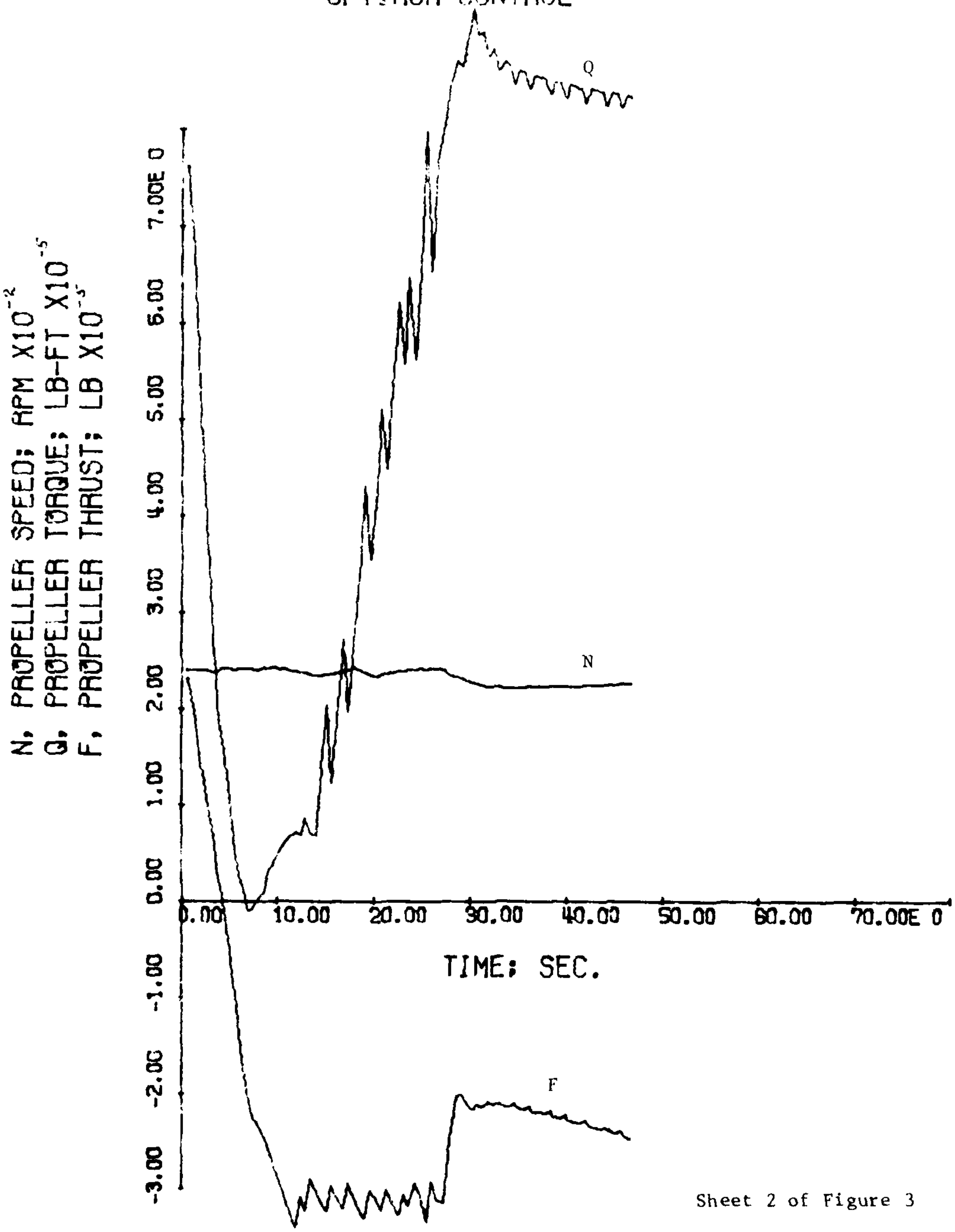
Crane's objective was to design a flexible control system using the US Navy's Standard Electronic Modules (SEM) which would demonstrate the effectiveness of digital electronics for use in the control of stabilizer fins. This evaluation was determined to be necessary since the Navy was considering specifying digital stabilizer control systems in both new hulls and in the retrofit of existing ships.

The Crane control system was designed to allow digital implementation of control laws similar to those which have been successfully used by previous electromechanical and analog control systems such as the Muirhead Limited system originally installed aboard the USS Glover and the prototype system described by reference (1) respectively. The design task was considered to be one of implementation rather than derivation of stabilizer control theory. The digital system was also intended to provide improvements over previous systems in the areas of automatic control and monitoring of the hydraulics system, self-test, fault isolation, reliability, and logistics support.



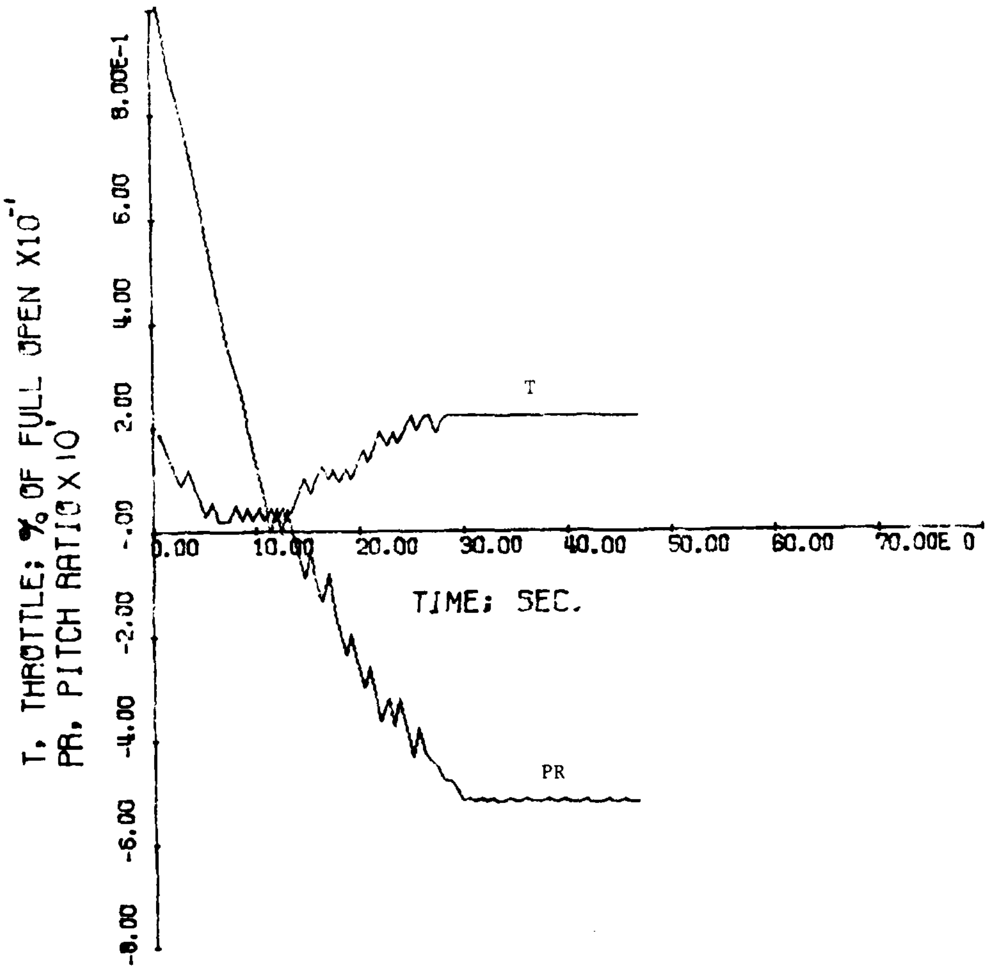
Sheet 3 of Figure 3

PROPULSION SYSTEM RESPONSE
TO CRASH STOP COMMAND
UNDER
OPTIMUM CONTROL



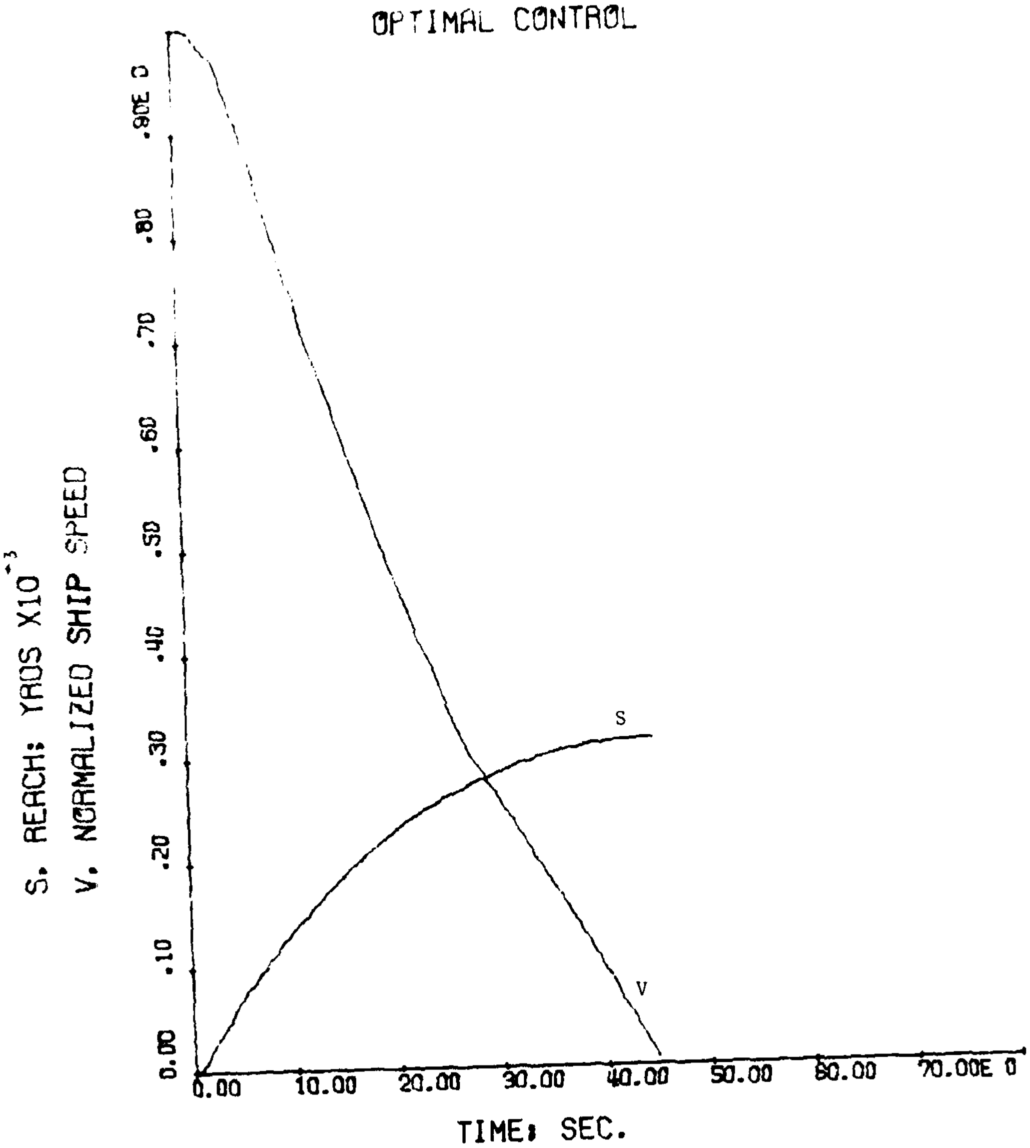
Sheet 2 of Figure 3

OPTIMUM PITCH-THROTTLE SCHEDULING
FOR
CRASH STOP MANEUVER



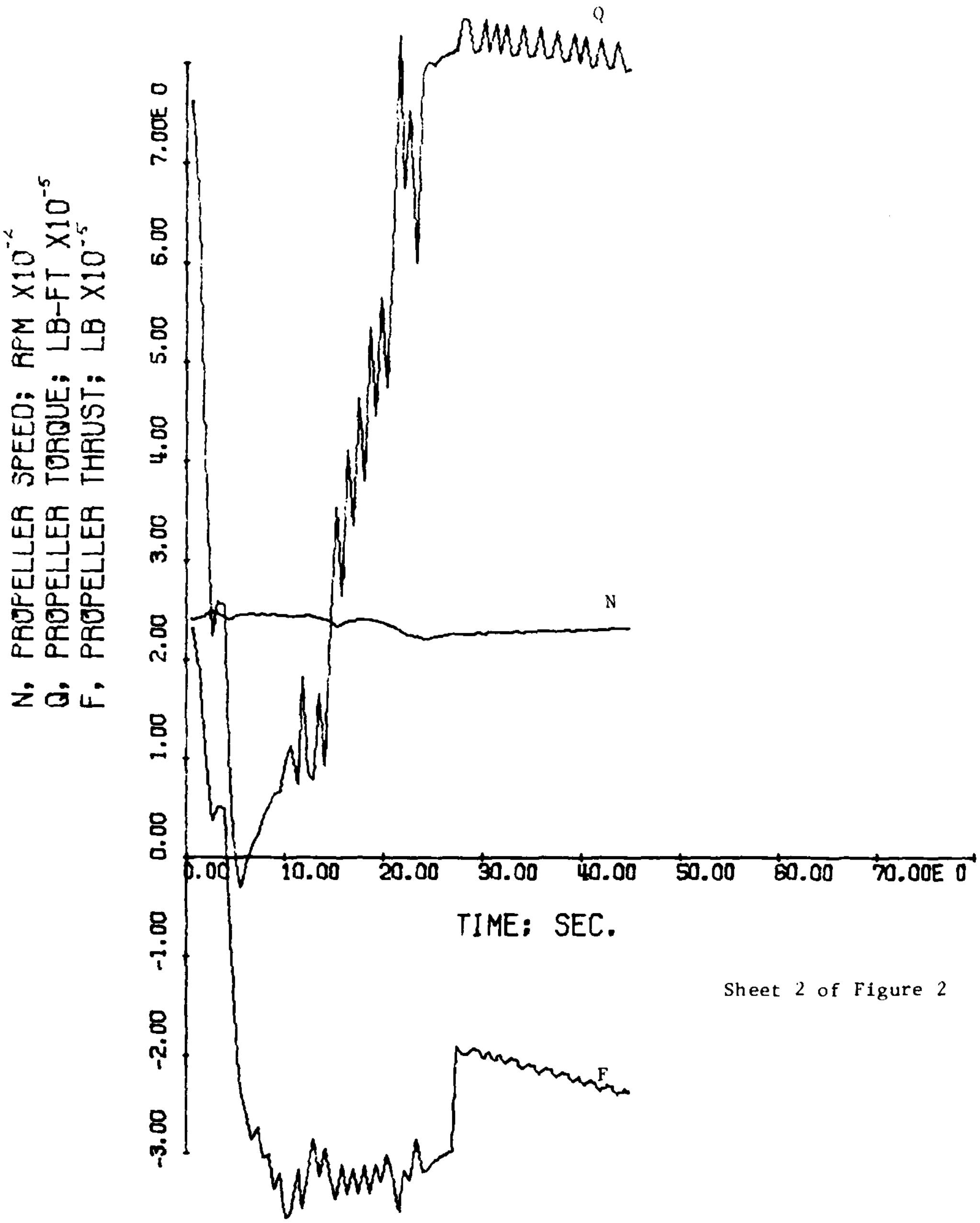
Sheet 1 of Figure 3

SHIP RESPONSE
TO CRASH STOP COMMAND
UNDER
OPTIMAL CONTROL



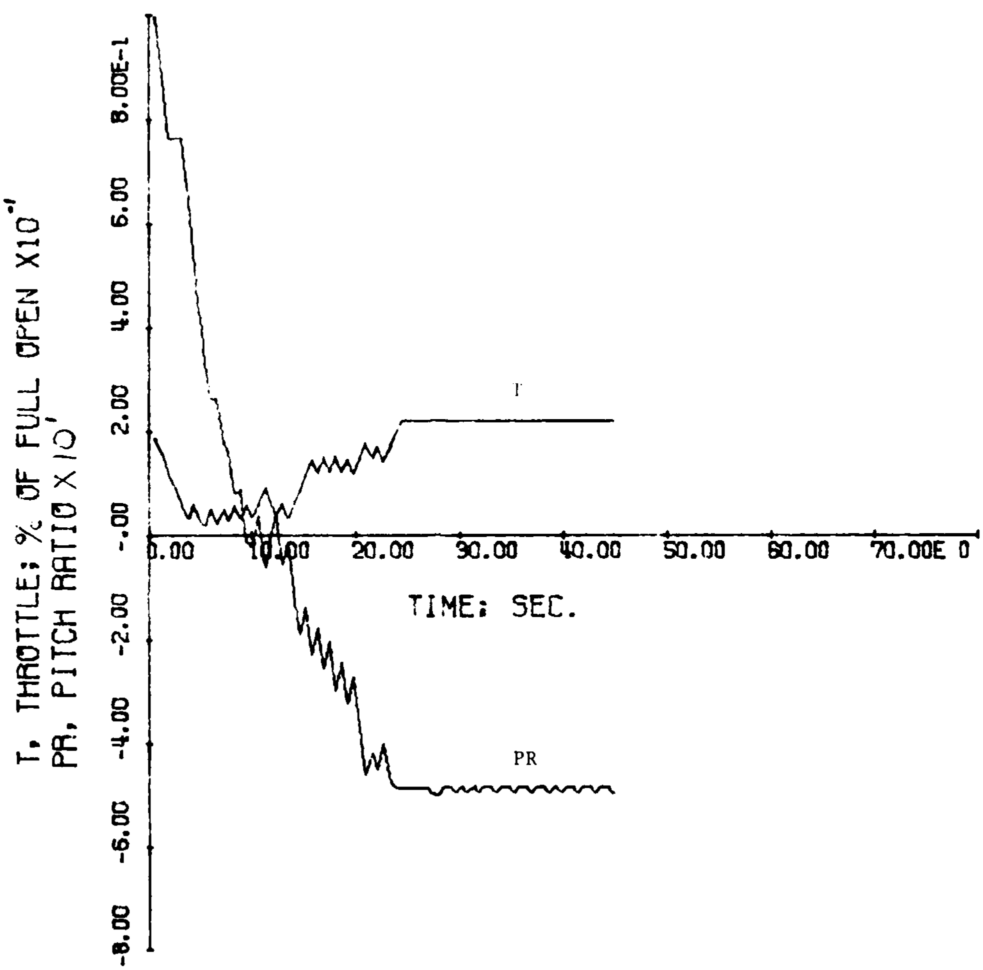
Sheet 3 of Figure 2

PROPULSION SYSTEM RESPONSE
TO CRASH STOP COMMAND
UNDER
OPTIMUM CONTROL

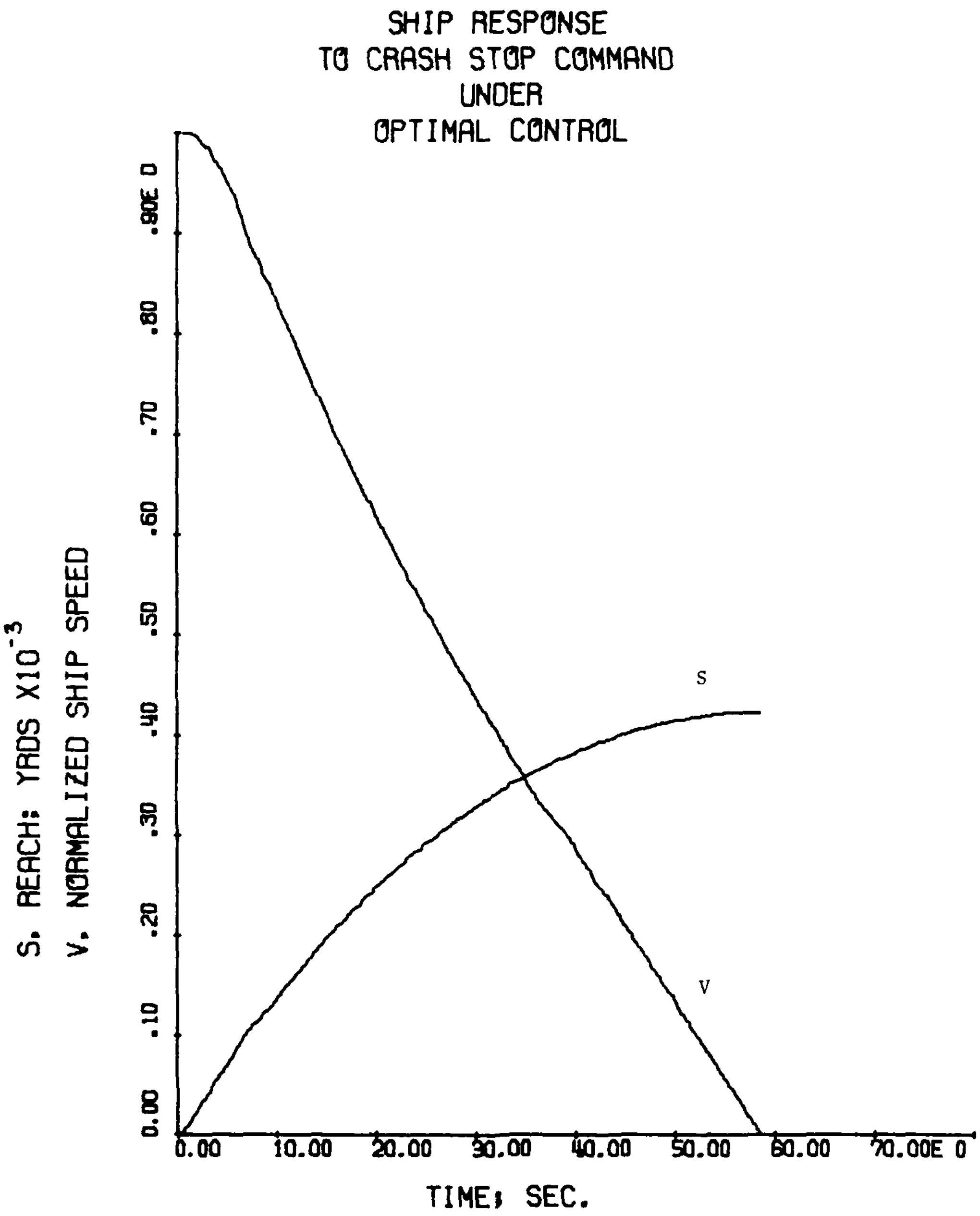


Sheet 2 of Figure 2

OPTIMUM PITCH-THROTTLE SCHEDULING
FOR
CRASH STOP MANEUVER



Sheet 1 of Figure 2



Sheet 3 of Figure 1

PROPULSION SYSTEM RESPONSE
TO CRASH STOP COMMAND
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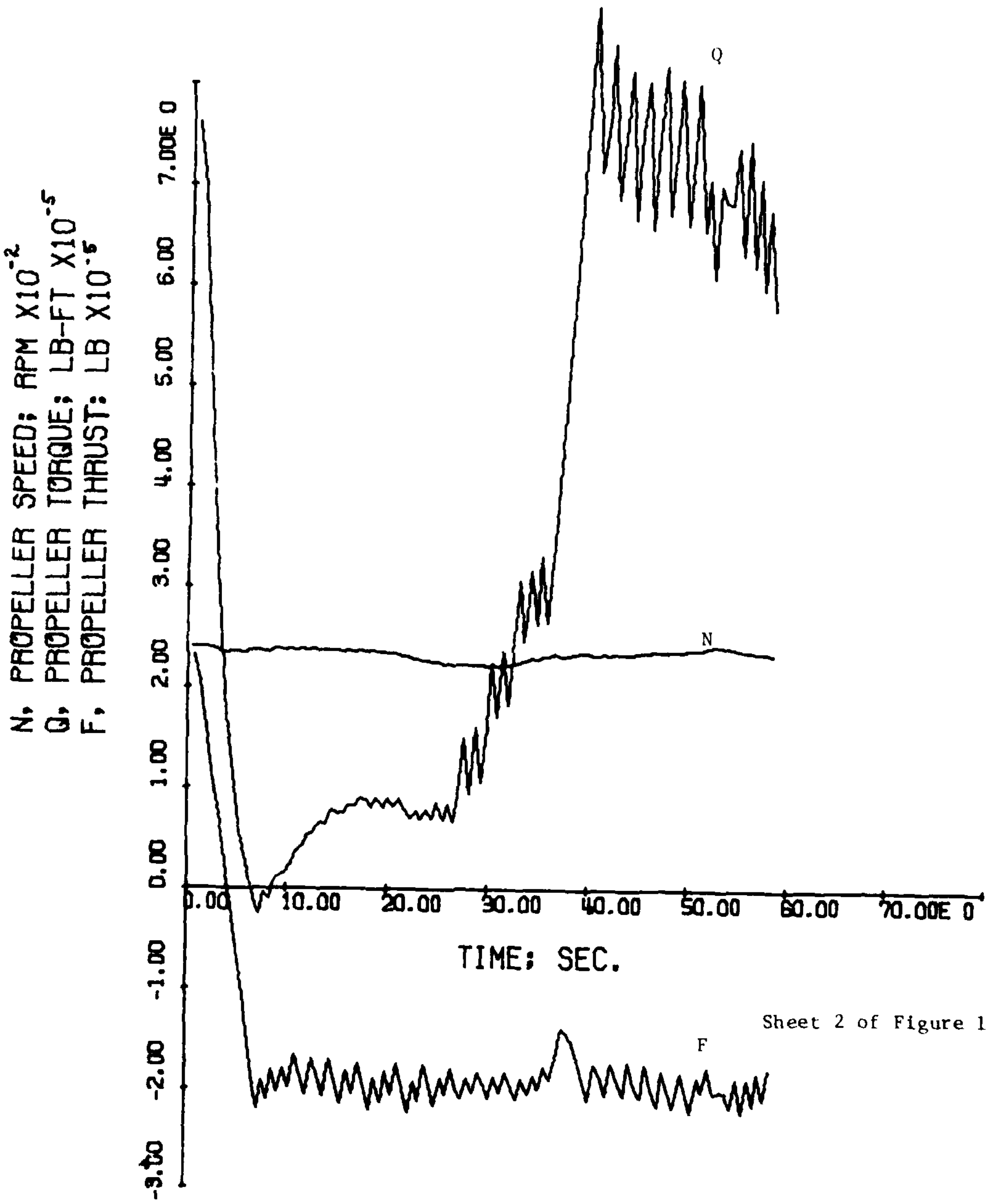
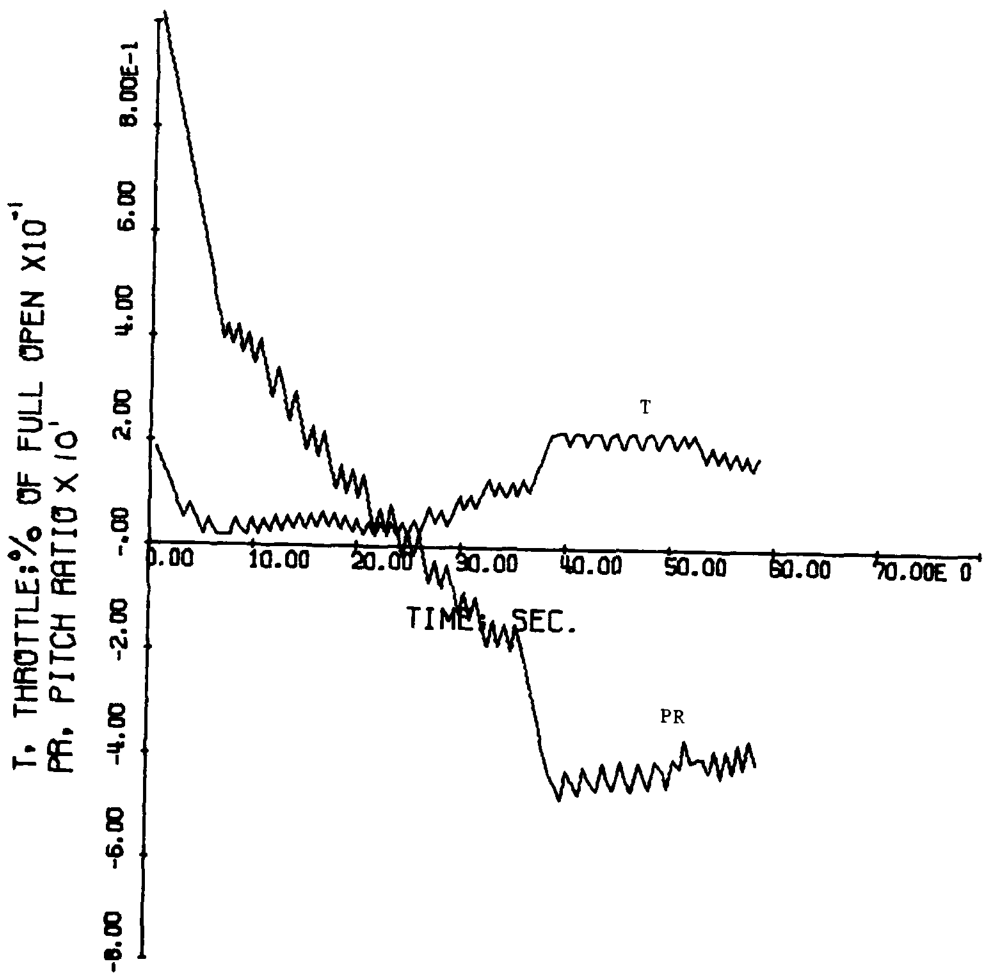


Sheet 2 of Figure 1

OPTIMUM PITCH-THROTTLE SCHEDULING
FOR
CRASH STOP MANEUVER



Sheet 1 of Figure 1

CONCLUSIONS

The optimal control algorithm for ship braking features closed loop control of propeller thrust and speed. The thrust and shaft speed setpoints are constrained to equal respectively the astern thrust bearing transient load limit and the full power speed of the propeller. The dynamic capabilities of the CRP propeller are exploited to achieve early and continued satisfaction of the thrust loop throughout the entire ship maneuver. Shaft speed is maintained at its highest "safe" value to provide the greatest possible thrust change to pitch change ratio further enhancing the thrust response to pitch changes. The quickest stopping time and the shortest stopping distance are thus assured. Although the algorithm was applied to a simulation of a steam powered combatant, it is probably better suited to the control of ships with propulsion systems that are capable of responding at least one order of magnitude faster than the ship. Gas turbine powered combatants and large steam or diesel powered vessels (tankers) are in this category.

REFERENCES

(2) C. J. Rubis, "CRP Propeller Ship - Propulsion Dynamics", Vol. 1 Report 3238 Feb 1971, Naval Ship Research and Development Center, Annapolis, MD 21402

(3) J. P. Comstock (Editor), "Principles of Naval Architecture", The Society of Naval Architects and Marine Engineers, New York 1967, p. 387

The most conservative pair of values used for K_p and $\hat{F}_a$ led to the production of the curves shown in Figure (1). The thrust (Sheet 2) uniformly decreases with time until it reaches its setpoint value, $\hat{F}_a$ at which time the slope of the pitch ratio curve (Sheet 1) is caused to decrease to a value consistent with maintaining a constant thrust while the ship slows (Sheet 3). The propeller shaft torque (Sheet 2) undergoes a temporary torque reversal at approximately the same time that the thrust first matches its setpoint. The magnitude and duration of the torque reversal are sufficiently small to preclude an apparent shaft speed increase. Shaft speed is nominally constant throughout the entire maneuver, a not too surprising a result in asmuch as that variable is control constrained to its full power value. The excursions of the steam throttle valve (Sheet 1) ensure satisfaction of the speed control loop in spite of the rapidly changing propeller load. The steepest rise in the torque curve (Sheet 3) begins at approximately the same time (35 seconds into the maneuver) that the peculiar "hump" in the thrust curve manifests itself, and the sudden large change in the slope of the propeller pitch ratio curve (Sheet 1) occurs. Evidently, the steep torque rise is a direct result of the correspondingly rapid pitch change. Since the pitch ratio is directed by the algorithm to provide a constant thrust, the sudden precipitous decrease in pitch must have been a consequence of a discontinuity in thrust. (The model thrust coefficient curves that were used in the simulation are discontinuous at $J = .25$, $PR < 0$, and $V_s > 0$, a "line" that the braking maneuver must intersect at least once). Thereafter, no other anomalous behavior is apparent. The ship velocity finally reaches zero 58 seconds after the maneuver was initiated and in the interim progressed approximately 425 yards.

The curves in Figure (2) depict the system response with the thrust bearing load limit raised 60% higher than the value under which the curves in Figure (1) were generated. There was an attendant significant decrease in ship stopping distance (336 yards from 425 yards) (Sheet 3) but the percentage change, 21%, was somewhat less than the expected reduction. The principal cause for the disparity between the expected and actual results was attributed to the increase in the magnitude of the discontinuity in thrust (Sheet 2). No other unusual or unique events were in evidence in this set of system responses.

The 60% increase in the thrust bearing load limit was combined with a 75% increase in the maximum pitch ratio rate to provide not only a relatively robust astern thrust bearing, but a quick pitch changing mechanism as well. The responses of the system with these particular system constants are exhibited in Figure (3). Note that the full astern thrust (Sheet 2) is achieved in approximately 8 seconds. This contrasts with the thrust curve in Sheet 2 of Figure (2) which shows that the thrust requires 12 seconds to achieve its setpoint. Ship stopping distance was 313 yards, which represents a total reduction in reach of 26%, 5% of which is directly attributable to the 75% increase in the pitch stroke rate.

The responses of the optimally controlled ship simulation and the corresponding actual responses of the ship invite comparison. However, the dynamics of the steam generator were not incorporated into the ship simulation. These dynamics may have required that severe rate constraints be imposed on the steam throttle valve necessitating a commensurate reduction in pitch stroke rate to avoid the possibility of turbine overspeed. For this reason, a direct comparison of ship trial results with simulation results is not valid. Nonetheless, it is of interest to note that the minimum stopping distance that was achieved in the simulation studies under optimal control was approximately one-half the measured ship reach for the same maneuver.

related to PR (t+ΔT) (the "closest" physically realizable approximation to PR_D that can be achieved in a time, ΔT) by the following equation.

$$PR\ (t+\Delta T) = PR(t) + K_p \Delta T\ SGN\ (PR_D - PR) \qquad (16)$$

Direct application of PR (t+ΔT) may result in an unacceptably large value of pinion torque. Accordingly, this candidate value for pitch ratio must be tested mathematically before it is actually applied to determine whether it will violate the torque constraint. The propeller torque, Q_p (t+ΔT) that would result from the pitch ratio, PR (t+ΔT) is defined implicitely by a relationship similar to equation (15).

$$Q_p\ (t+\Delta T) = Q_p\ (PR(t+\Delta T),\ N_p(t),\ V_s\ (t)) \qquad \text{lb ft} \qquad (17)$$

If Q_p (t+ ΔT) exceeds the torque limit, $\hat{Q}_p$, then pitch ratio is commanded to remain "fixed" in the interval, ΔT. In fact, pitch ratio is permitted to be indexed toward its optimal value only if Q_p (t+ΔT)< $\hat{Q}_p$ and the current value of propeller speed $N_p(t)$ is not too close to its overspeed value, $\hat{N}_p$.

The requirement that propeller speed be constrained to be less than its overspeed value is satisfied by "closing the loop" on propeller speed and by regulating that speed with the steam throttle valve. The setpoint for that control loop was chosen to be equal to the full power speed to provide a high propeller (or equivalently high engine) speed and some relatively small overspeed margin. This choice of speed setpoint was based on the fact that thrust monotonically increases with decreasing values of ship speed and increasing values of propeller speed so that the maximum attainable thrust at any ship speed occurs at maximum propeller speed. With speed nominally constant (N_p = 0), the propeller load approximately matches the total torque produced by the main engines. Accordingly, the steam flow rate, W_S (t+ ΔT) required to maintain constant propeller speed is related to the propeller torque, Q_p (t+ΔT) in accordance with equation (5).

$$Q_p\ (t+\Delta T) \simeq Q_a(N_p(t),\ W_s\ (t+\Delta T)) \qquad \text{lb ft} \qquad (18)$$

The number of throttle turns, TT_D corresponding to that steam flow rate can be determined from equation (12).

$$W_s\ (t+\Delta T) = W_s\ (TT_D) \qquad \text{lb hr}^{-1} \qquad (19)$$

The solution TT_D of equation (19) can then be used to specialize the general solution to equation (13) thereby yielding the appropriate number of throttle turns, TT (t+ΔT).

$$TT(t+\Delta T) = TT(t) + K_{TT}\Delta T\ SGN\ (TT_D - TT) \qquad \text{turns} \qquad (20)$$

RESULTS OF THE SIMULATION

The propulsion control algorithm and the ship powering equations were linked mathematically to form a system that was mechanized on NAVSECPHILADIV's digital computer system. The resulting real-time simulation was then used to generate the three sets of performance curves depicted in Figures (1), (2) and (3). All three sets of curves show the response of the ship simulation under optimal control to a Crash Astern maneuver from a Full Ahead steady-state condition. Differences in corresponding curves from one set to another are attributable to the differences in the values selected for the two "constants": astern thrust bearing load limit, $\hat{F}_a$ and maximum pitch ratio rate, K_p. The overspeed and overtorque thresholds and the throttle valve stroke rate were "fixed".

The system is required to interface with two existing ship's systems, the gyrocompass (MK 19 on the USS Glover) for ship's roll angle data and the electromagnetic (EM) log for ship's speed data. These existing systems both provide their respective data in synchro format.

A photograph of the Crane prototype system hardware is included as Figure 2. The equipment enclosures shown are the Central Control Unit (CCU) (foreground), Central Processing Unit (CPU) (door closed), and a Local Control Unit (LCU) (door open). The mechanical and thermal designs for the equipment pictured were completed at Crane as was all fabrication and assembly.

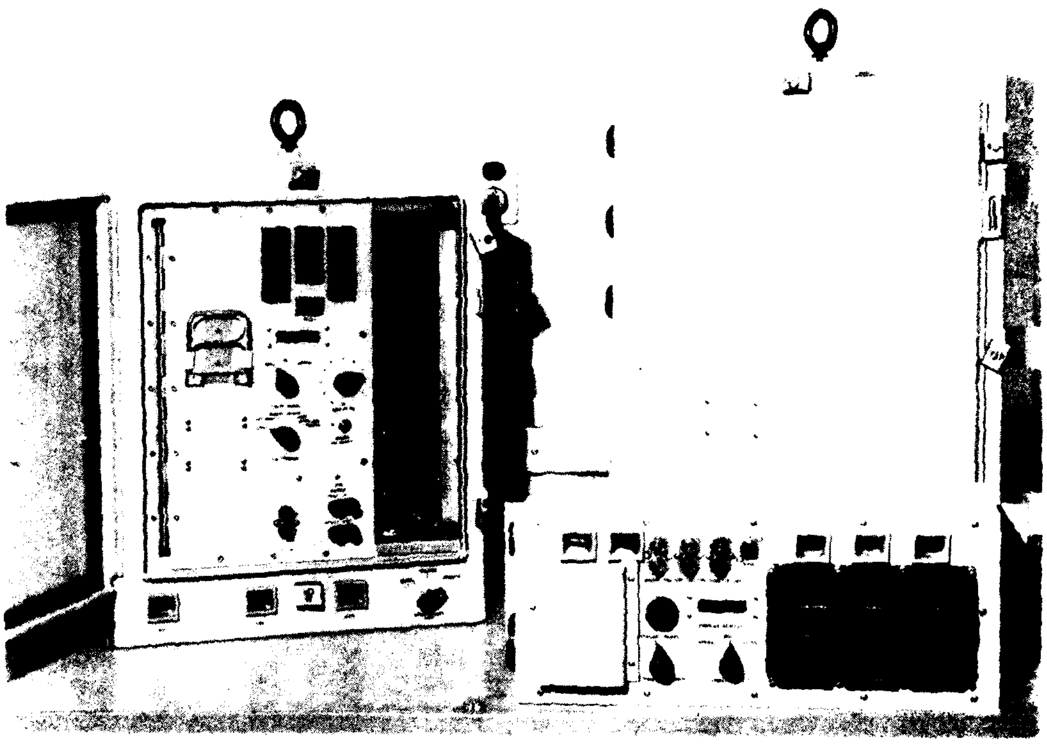


Figure 2. Prototype System

Drawings of the control and display panels for the Bridge Control Unit (BCU), the CCU, and the LCU are included as Figures 3, 4, and 5, respectively so that the details of these panels can be more easily observed. It should be noted that the BCU panel is essentially used twice with the system since it also is integrated into the CCU. The port and starboard LCU are identical to provide additionally commonality within the system. The CPU will be described in detail below; however, a drawing is not included since the only control contained within the unit is a power off/on switch.

A fairly complete understanding of the level of control and monitoring which is possible from each of the above units is attainable by studying Figures 3, 4, and 5, in conjunction with the performance information provided in the SOFTWARE IMPLEMENTATION section of this paper.

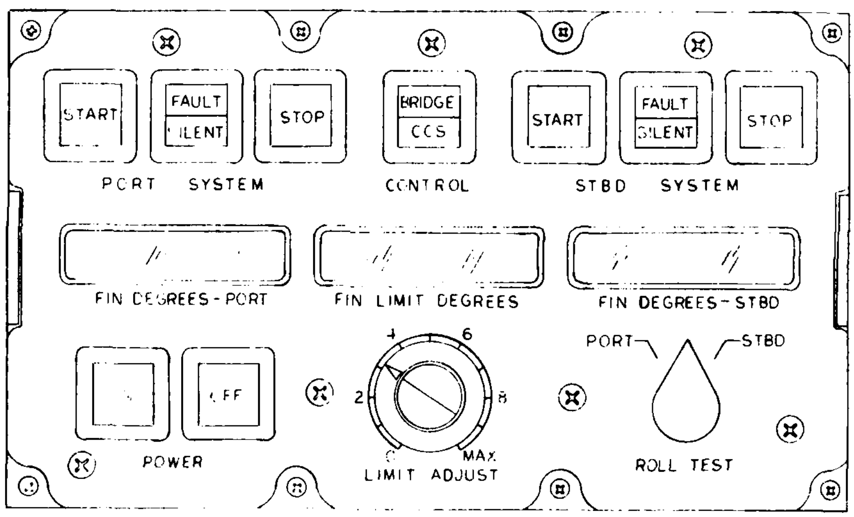


Figure 3. Bridge Control Unit

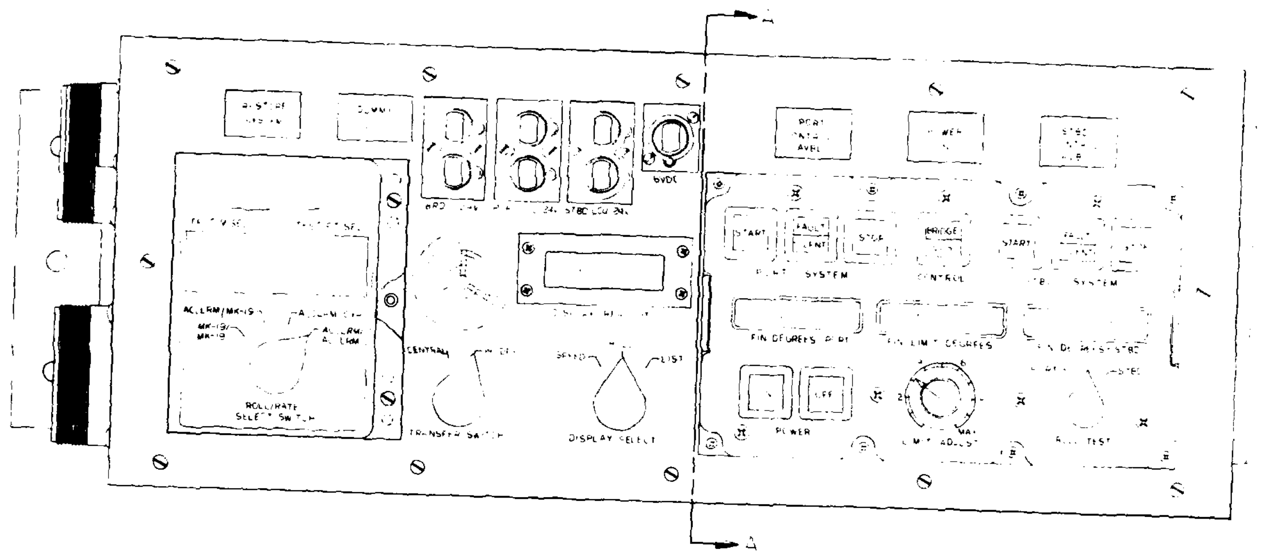


Figure 4. Central Control Unit

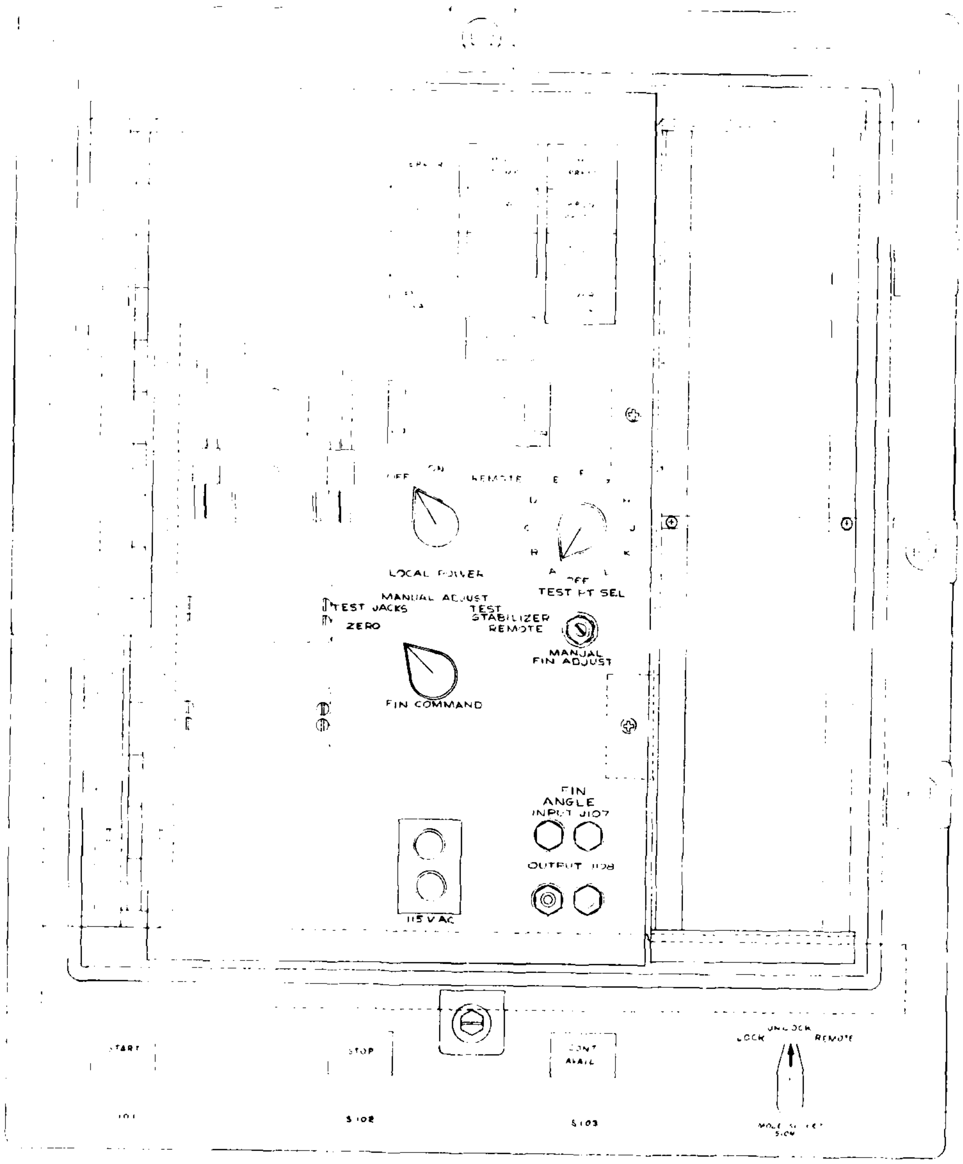


Figure 5. Local Control Unit

Central Processor Design

The CPU is the subsystem which is responsible for monitoring and executing almost all stabilizer fin control system functions. This unit consists of a microprocessor controlled system which is capable of operating in several different modes depending upon which control settings are selected by the operator and whether or not malfunctions have been detected in the system.

The CPU is required to accept synchro signals from the ship's gyrocompass and EM log; analog signals from the linear accelerometer and rate gyro among others; control switch closure signals and relay closure signals. The unit executes all data process- requirements and functions detailed in the System Software Operation section below and provides output interfacing including analog fin command signals, display driving, digital signals, and relay signals for hydraulic pump motor control.

A block diagram of the CPU is included as Figure 6.

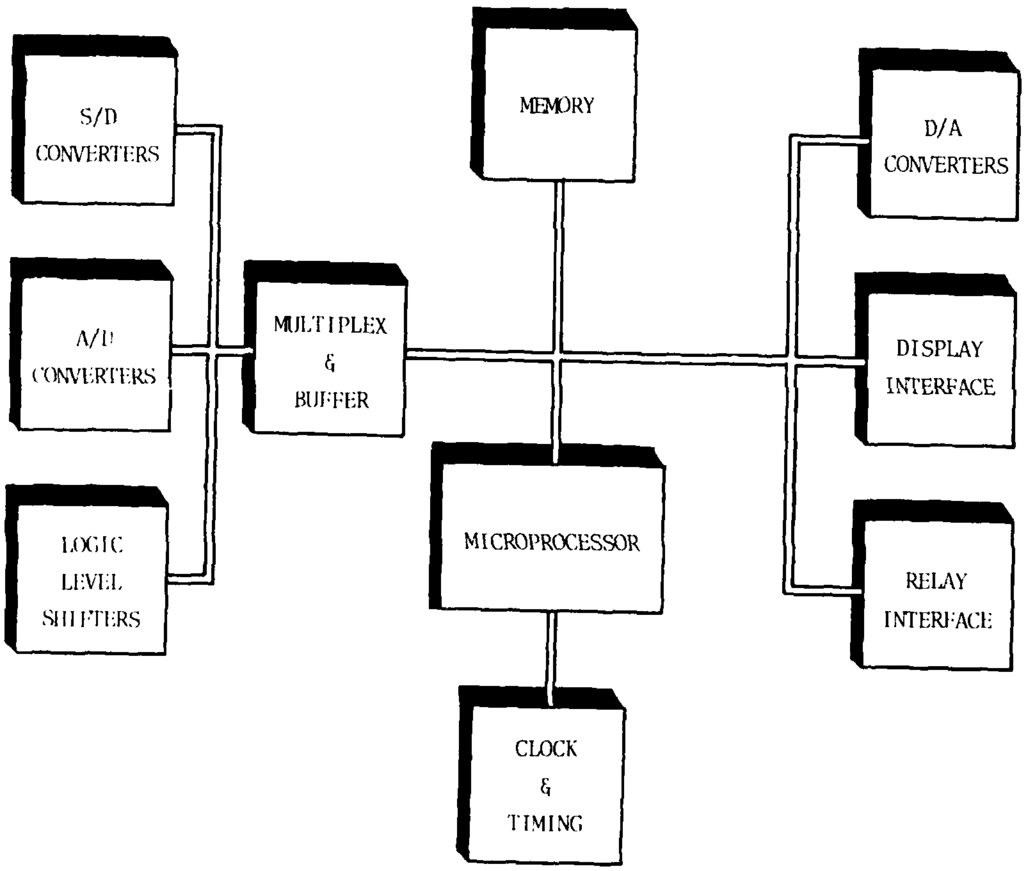


Figure 6. Central Processor Unit Block Diagram

The system computer is an 8-bit NMOS 6800 microprocessor which is driven by a two phase 1.3 microsecond clock signal.

Interrupts are provided to the microprocessor every 8 milliseconds in order to allow real time data processing and the generation of precise timing intervals.

The prototype system has 4096 words of 8-bit program memory and 1024 words of 8-bit random access memory for use as scratchpad type storage. Ultraviolet light erasable read only memories (EROMs) were used for prototype system program memory with the intent of replacing them with programmable (non-erasable) memories after completion of program development. Input data is selected by the microprocessor using multiplexer circuitry which routes one of the 15 8-bit input data ports onto the tri-state data bus which interconnects the microprocessor, the memory, and the latches for the 10 8-bit output latches.

The electronics required for the CPU was implemented using the US Navy's Standard Electronic Modules (SEM). As a result of using SEM in the CPU it was possible to purchase 72 modules out of a total of 75 from established industry vendors. Two of the three non-standard modules are for use in the development system and would not be required in a production system. Since the modular electronics was available off-the-shelf, it was possible to delete the integrated circuit level design and procede dirctly to the wirewrapped backpanel, modular design as the first (and last) development model. SEM usage also simplified system documentation since almost all of the modular electronics was fully documented by the SEM Program.

Standard Electronic Modules

Standard Electronic Modules were used in both LCUs in addition to the CCU described above. This section provides a brief summary of the SEM program.

Objectives. The basic objectives of the SEM program follow:

- Partitioning of electronic functions so that modules are common to many equipment applications
- Documentation of modules with functional specifications to allow multiple vendor sourcing of designs
- Achieving high reliability through stringent quality assurance requirements for module design and production
- Providing flexible modular mechanical packaging configurations applicable to various circuit packaging technologies and equipment platforms
- Discarding modules on failure because of high reliability and low module cost

Organization. The SEM program is organized with the Naval Electronic Systems Command designated as the technical management activity; the Naval Avionics Center, Indianapolis, Indiana, as the design review activity; and the Naval Weapons Support Center, Crane, Indiana, as the Quality Assurance Activity. SEM design requirements are covered in MIL-STD-1389 while MIL-M-28787 is the general specification for modules and is organized with a slash sheet for each individual electronic function module.

SEM Status. Approximately 300 module types have been identified as standards with about 4 million SEM now committed to production. These modules have been applied in over 75 major electronic systems used by the Navy, Army, Air Force, NASA, and also in systems used by several other nations including the United Kingdom, Australia and France.

Representative of major system applications are the following:

. MK-88	Poseidon Fire Control System
. AN/BQQ-5 and 6	Sonar Systems
. AN/BQR-21	DIMUS Sonar
. MK-98	Trident Fire Control System
. AN/BRR-3	Frequency Shift Keying (FSK) Demodulator
. AN/APG-19	Radar System

Most SEM designs are applied in multiple systems with several functions being used in more than ten major systems each. Modules are currently available from over 20 qualified vendors, with multiple industry sources available for most standard functions.

A wide range of semiconductor of technologies including TTL, NMOS, CMOS, and I^2L is available in SEM. The families of available circuit functions include digital logic, interface circuits, A/D and D/A converter modules, S/D converter modules, relays, analog filters and amplifiers, microprocessors, memories, clock/timing circuits and power supplies.

New developments being pursued under the SEM Research and Development Program include improvements in the modular configuration which will result in additional circuit mounting area, additional contact pins, and improved thermal capacity. Innovations such as these and new functions such as the 16-bit Integrated Injection Logic (I^2L) chip carrier microprocessor module which includes clock and timing, power-up/restart logic, full buffering on data and address busses, 4096 words of 16-bit program memory, 1024 words of 16-bit random access memory, a parallel input/output port and an interrupt controller are making SEM particularly useful in high density, space limited applications. A prototype of this microprocessor module is shown in Figure 7.

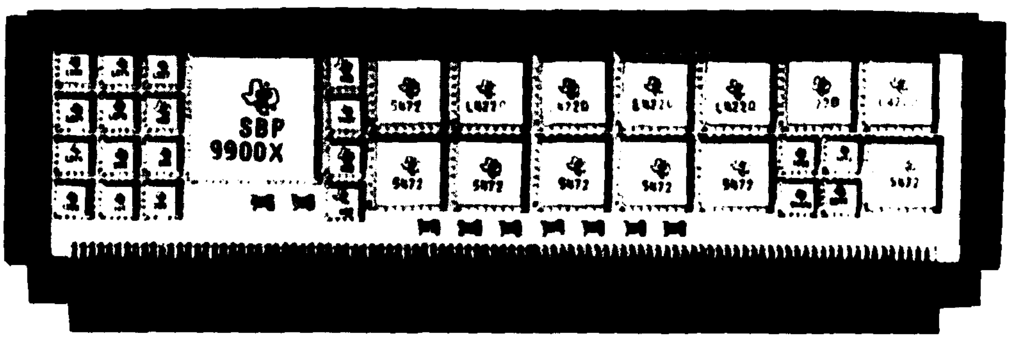


Figure 7. Prototype 16-Bit SEM Microprocessor Module

SOFTWARE IMPLEMENTATION

Development Approach

The development of software for the USS Glover system was accomplished using a structured approach. The following sequence of events was performed in order to minimize the difficulty of program development by maintaining as much flexibility as possible during all phases of the design task:

(1) Defined required software performance for the stabilizer system in relation to overall system operating requirements.

(2) Established flow diagrams showing the software functions to be performed and how each block of software was to interrelate with all other blocks. A simplified master flow diagram for the system is shown in Figure (8).

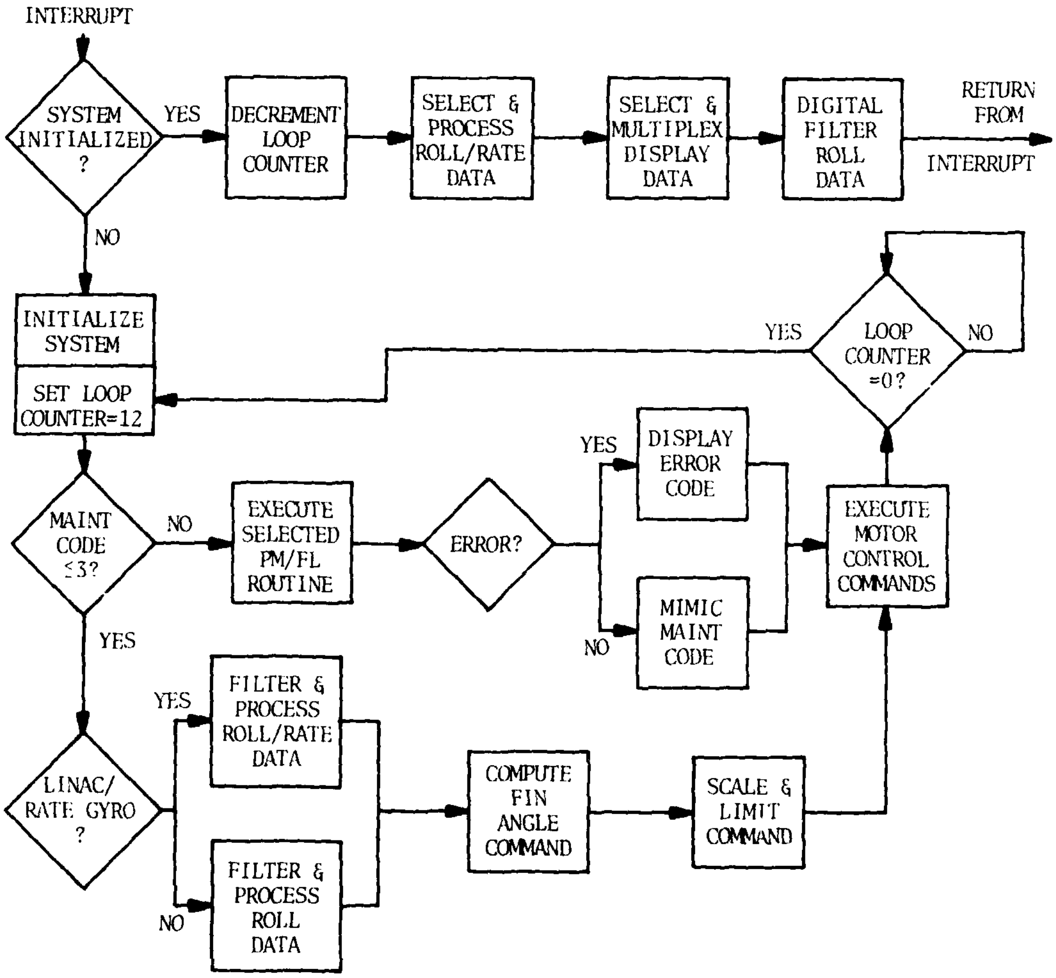


Figure 8. Software Flow Diagram

(3) Programmed each of the subroutines or blocks of software indicated on the flow diagrams using mnemonics or microprocessor source code.

(4) Assembled the source code into object code (logical "ones" and zeroes") which is recognizable by the microprocessor using resident assembler software on a portable development microcomputer.

(5) Performed initial testing of the software using the development microcomputer to simulate the operation of the microprocessor to be used in the CPU.

(6) Performed secondary testing of the software using a differential interface designed in-house which allowed the development microcomputer to control the prototype stabilizer fin control system directly from distances of up to 20 feet. This interface allowed immediate changes to operating software (via a digital data terminal keyboard associated with the development microcomputer) while identically simulating final system functional operation. This mode of operation was actually used during initial sea trial testing to allow rapid software troubleshooting and modifications to the program.

(7) Installed software (object code) in the EROMs previously described. These memory devices allow the system to operate the same as the final system, but offer the advantage of being erasable and reprogrammable by the development microcomputer in a matter of minutes.

(8) The final step will be to install object code in mask or fused link programmed read only memory microcircuits when system development is completed.

System Software Operation

Overview. The software which controls the fin stabilizer system is essentially segmented into five areas:

(1) Roll Data Input and Display Update
(2) Data Processing
(3) Fin Angle Computation
(4) Execution of Motor Commands
(5) Maintenance/Fault Location

While in normal operation roll data inputting and display updating is accomplished once each 8.0 mSec; data processing, fin angle computation, and execution of motor commands are done once each 96.0 mSec; and the maintenance/fault location software functions are executed when one of the two following conditions exist:

(1) A fault is detected by the control system.
(2) The operator initiates specific maintenance/fault location routines.

Reference to the drawing of the CCU (Figure 4) is required throughout this section in order to understand the use of various operator control switches and indicators. The nomenclatures associated with these switches and indicators are presented in capital letters in this paper. Reference to the software flow diagram shown in Figure 8 will also be helpful.

Roll Data Input and Display Update. An interrupt pulse is provided to the microprocessor every 8.0 mSec in order to initiate execution of this segment of the software. Upon receiving this pulse the microprocessor checks an internal random access memory location which is used as a flag to indicate whether or not the system has been initialized.

The initialization process basically consists of the following steps:

(1) Set all outputs to the quiescent state. (Set fin angle command to zero degrees, set the fin hydraulic locks, etc.)

(2) Clear all random access memory locations.

(3) Reset cycle counter to twelve. This counter is decremented once each 8.0 mSec and will initiate execution of data processing, fin angle computation, and motor commands each 96.0 mSec.

This initialization process is completed prior to execution of any of the data processing or computation software. The microprocessor then interrogates the ROLL/RATE SELECT SWITCH and performs the timing and control operations necessary to input the current roll and/or roll rate data from the selected source. The data is obtained from either the synchro-to-digital or analog-to-digital converter as appropriate and is properly formatted and stored for later use.

The DISPLAY SELECT SWITCH is then interrogated and the selected data (speed, roll angle, or list angle) is formatted for binary-coded-decimal display, converted to seven-segment code and software multiplexed to the DISPLAY READOUT. One of the three displayed decimal digits is multiplexed each 8.0 mSec resulting in a display update each 24.0 mSec.

The roll data is then digitally filtered using a software implemented 1 Hz bandwidth low pass filter to attenuate noise. The microprocessor then waits for the next 8.0 mSec interrupt at which time the entire Roll Data Input and Display Update sequence is repeated.

Data Processing. Following each twelve successive 8.0 mSec interrupts the cycle counter is decremented to zero which initiates the 96.0 mSec program cycle (12 X 8.0 mSec). This cycle normally consists of data processing, fin angle computation, and motor command execution. Upon entering the 96.0 mSec program cycle the cycle counter is reset to twelve. The TEST M SEL switch is then interrogated to determine if specific maintenance routines have been selected by the operator. If no maintenance routines have been selected the data processing segment of the software is entered.

The data processing software is subdivided into two major sections. The ROLL/RATE SELECT SWITCH is interrogated in order to determine the selected source of roll/rate data. If the ACCLRM/GYRO source is selected the roll rate data is processed through a low pass digital filter with a bandwidth of approximately 0.7 Hz and then is further filtered by an averaging subroutine to obtain ships roll rate. The first derivative of this value is then computed to obtain roll angle acceleration. A software routine is provided to remove any D. C. offset present in the gyro data. The roll angle data from the linear accelerometer is then processed through the 0.7 HZ digital lowpass filter. If either MK-19/MK-19, ACCLRM/MK-19, or ACCLRM/ACCLRM data is selected using the ROLL/RATE SELECT SWITCH, the microprocessor will first process the ship's roll angle data (which is either from the linear accelerometer or the ship's gyrocompass) through the 0.7 Hz lowpass digital filter. The first derivative and second derivative of this filtered roll angle data are then computed in order to obtain ship's roll angle rate and ship's roll angle acceleration data.

The data processing segment of the software therefore provides formatted roll, roll rate, and roll acceleration data for the fin angle computation software regardless of the data source selected. This final data as well as intermediate and past values of final data is stored in random access memory for later use by various filters as well as the fin angle computation software.

Fin Angle Computation. This segment of the functional software performs an offset subroutine using ship's roll angle data in order to determine the ship's list angle. This list angle data is stored in memory and is the data displayed when the DISPLAY SELECT switch is positioned to LIST. The roll angle is then extracted from the listed roll angle and the net roll angle is stored. This data is displayed when the DISPLAY SELECT Switch is positioned to ROLL.

The magnitude of ship's roll angle is then compared to the magnitude of the ship's roll angle acceleration in order to determine whether the ship is in a beam or a quartering sea. An appropriate set of constants is then selected from program memory and the fin angle command (FAC) is computed:

$$FAC = C_1\theta + C_2\dot{\theta} + C_3\ddot{\theta}$$

where θ = ship's roll angle

$\dot{\theta}$ = ship's roll rate

$\ddot{\theta}$ = ship's roll acceleration

The sets of constants are selectable so as to allow choosing the phase difference between the ship's roll angle and the fin angle command and to allow programmable system gain in 3dB steps.

The maximum fin angle commandable is then computed as a function of the LIMIT ADJUST control and the ship's speed. This data is displayed on the FIN LIMIT DEGREES readout and is also stored for later use. This data is also used as the port and starboard stroke limit signal.

The computed fin angle command is then scaled as a function of ship's speed and an automatic gain control scale factor which is incremented or decremented, based on whether the computed fin angle command is less than or greater than, respectively, the maximum fin angle commandable. This results in the control of the fins being a smooth and continuous command signal rather than allowing a limit-to-limit operation. This scaled value is then compared to the calculated maximum fin angle command and the angle of lesser magnitude is provided by the central processing unit as the starboard and port fin angle commands.

The ship's speed data is also converted, formatted, and processed by a 0.7 Hz lowpass digital filter by this segment of software. This filtered data is used to limit and scale the computed fin angle command as a function of ship's speed and is also the data displayed when the DISPLAY SELECT switch is positioned to SPEED.

Execution of Motor Commands. This section of the software monitors hydraulic pump status and control switches and executes the resulting commands. A software switch debounce procedure is applied to all switch inputted signals to prevent false decoding of control commands. The following functions are executed by this section of software:

(1) Port or Starboard System Start. Depressing the PORT SYSTEM or STBD SYSTEM START switch will result in the execution of the following startup sequence for the selected system if the corresponding PORT CONTROL AVBL or STBD CONTROL AVBL indicator is lit indicating remote control is available for the LCU:

a. The port or starboard motor will be commanded "on" as indicated by the depressed START switch if the corresponding CONTROL AVBL indicator is lit.
b. A 3.0 second delay is initiated.
c. The motor on command will be removed.

(2) Port or Starboard Stop. Depressing the PORT SYSTEM or STBD SYSTEM STOP switch will result in the execution of the following shutdown sequence for the selected system if the corresponding PORT CONTROL AVBL or STBD CONTROL AVBL indicator is lit:

a. Fin angle command of 0^{o} is sent to the fins.
b. A 3.0 second delay is initiated to allow the fins to zero.
c. Appropriate fin is hydraulically locked.
d. A 1.0 second delay is initiated.
e. Appropriate motor is turned off.
f. A 1.0 second delay is initiated.
g. Motor off command is removed.

(3) CPU Power Down. When the POWER OFF switch is depressed the above procedure for Port or Starboard Stop is executed for both fins. Following completion of this sequence, power is removed from the CPU.

(4) Control of PORT SYSTEM and STBD SYSTEM FAULT/SILENT Indicators and Switches. The PORT and/or STBD FAULT/SILENT indicator(s) will be lit as appropriate if the corresponding motor(s) is off without having been commanded off by the CPU.

(5) Shutdown Prevent Pulse Generation. A shutdown prevent pulse is generated by this section of software. This is done so that the system will be secured if the microprocessor loses the capability of controlling the system because of a fault. Failure of the microprocessor to generate this pulse for two consecutive 96 mSec program cycles will result in fin angle command of 0^{o} and the fault lights being lit.

Maintenance/Fault Location

The built-in-test capability of the system is generally provided by the Maintenance/Fault Location software. The following TEST M SELECT switch codes are currently executed by this software:

40 - Performs a checksum test of program memory modules and indicates specific defective module.
41 - Performs pattern testing and fault isolation of random access memory modules.
42 - Performs testing and fault isolation of Digital-to-Analog and Analog-to-Digital conversion circuitry using closed loop technique.
45 - Performs testing of control panel switches.
50 - Displays starboard FAC.
51 - Displays port FAC
52 - Displays starboard pump stroke limit.
53 - Displays port pump stroke limit.
55 - Displays rate gyro input data.
56 - Displays linear accelerometer input data.
57 - Displays port fin angle.
60 - Displays starboard fin angle.
61 - Displays input from LIMIT ADJUST control.
62 - Displays system ground.
63 - Displays system +5 volt power.

Any faults detected will result in display of a representative error code on the DISPLAY READOUT. As an example, the operator would dial in a 40 on the TEST M SELECT switch to initiate functional testing of the program memory modules. If an error is detected in one of the four modules an error code of either 40.1, 40.2, 40.3 or 40.4 would be displayed on the DISPLAY READOUT indicating which module to remove and replace. The code 40.0 would be displayed if no errors were detected.

SEA TRIALS

System Features Facilitating Testing

The use of a microprocessor in the Crane system allowed the inclusion of several design features which were beneficial for testing the system both in the laboratory and at sea aboard the USS Glover. In addition to the use of the development microcomputer to directly control the system and the utilization of EROMs during underway testing, the following features provided flexibility during the testing period.

Control Law Programmability. The gain and phase characteristics of the control system are established by selecting constants C1, C2, and C3 described earlier in conjunction with the second order differential equation which is used to compute the fin angle command. Eight sets of these constants were preprogrammed into each of several EROMs. The selection of one of the eight sets was accomplished using an SEM switch module. A different group of 8 constant sets could be easily obtained by replacing the SEM EROM module containing the constants. Sets were typically programmed to allow varying gain and phase in steps of 3 dB. A slower secondary mode of constant selection (requiring changing of an EROM to execute) was also designed which allowed using the SEM switch module to directly input digitized values for each of the three constants.

Operation Mode Selection. Although any system mode of operation could have been selected or altered by replacing an EROM with one which had been programmed to implement the change, two such mode changes warranted dedication of SEM switch module positions in order to allow rapid mode selection during underway testing. A switch to either enable or disable (set to maximum) the automatic gain described earlier was assigned to allow evaluation of this adaptive control feature. Also, a switch position was used to indicate to the microprocessor whether to update the fin command during the 96 mSec cycle or the 8 mSec cycle.

Design Evaluation and Conclusions

Underway testing indicated that all major design features were functioning correctly. The capability to easily implement a wide variety of control law characteristics including emulation of the system response of the electromechanical control system aboard the USS Glover was demonstrated. Significant roll reduction in ship's maximum roll angle (as compared to unstabilized rolling) was documented on strip chart recordings. The primary purpose of the prototype system was, however, to evaluate the feasibility of a digital stabilizer fin control system and to evaluate its overall performance rather than specifically to optimize the control law. The following paragraphs are representative of the types of conclusions resulting from the evaluations.

(1) The updating of outputs at 8 mSec intervals results in a smoother fin command than the original 96 mSec update rate. Sufficient time is available to update at rates faster than 8 mSec if desired.

(2) Because the converters used in the system are either 12 or 16-bit devices, the use of a 16-bit microprocessor would be preferable, considering programming time requirements, memory requirements, and real-time processing speeds.

(3) Digital filtering should be further evaluated and bandwidths optimized. Particular attention should be given to the ship's EM log signal which tends to be very unsteady.

(4) It was determined that the microprocessor is only active about 30% of the total cycle time indicating that at great deal of additional data processing, filtering or functional performance could be added to the system without degrading performance.

(5) A faster response to switch closures (prototype system requires depressing switch buttons for about 3/10 second) is desirable from a human engineering standpoint.

(6) The use of digitally multiplexed displays such as the one located in the CCU appears preferable to displays in the system which have integral Analog-to-Digital converters for both display stability and cost reasons.

Following successful completion of underway testing, the system remained aboard the USS Glover so that information could be gathered regarding system performance, operability and maintainability under normal fleet operating conditions as opposed to sea trial testing. The benefits of digital control of stabilizer fins have been demonstrated as being significant by this project and digital design efforts have been initiated by the US Navy (Reference 2) for application on new hulls.

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AD-A159 085 PROCEEDINGS OF THE SHIP CONTROL SYSTEMS SYMPOSIUM (5TH) HELD AT U S NAVAL..(U) DAVID W TAYLOR NAVAL SHIP RESEARCH AND DEVELOPMENT CENTER ANN.. 3/3

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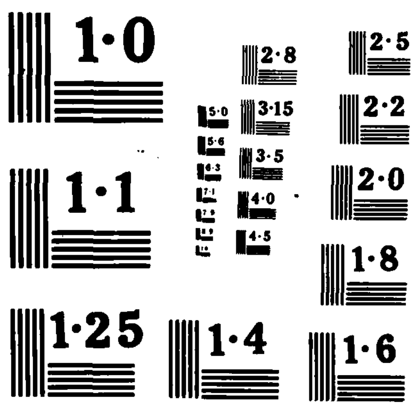
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THE USE OF MICROPROCESSORS IN SURFACE SHIP BRIDGE CONTROL SYSTEMS

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ABSTRACT

It is a usual requirement of complex shipboard systems that functional subsystems (modules) have autonomous, redundant and cooperative modes of operation. This can create complex layers of control interfaces which cause significant difficulty in system design, debugging and maintenance. Careful analysis of requirements and interactions between subsystems can reduce complexities at the early stages of design.

This paper describes the design of a Surface Ship Bridge Control System. This system incorporates a number of microprocessor based subsystems or modules, interacting with each other and a mini-computer central controller. The design concepts utilized to reduce complexities in this system will be discussed.

INTRODUCTION

Significant goals for shipboard systems are modularity and design for change. Success is measured by long-term reliability and maintainability, which includes the capability to incorporate future changes. The use of microprocessors as controllers for modules of a complex system has become accepted practice. However, this does not insure the benefits of true modularity. The idea of simply burning a new read only memory to affect a change in a module is not always a reality. The development of the new software can be expensive. The software for each task must not only be correct in its algorithms and logic, but must also satisfy timing constraints due to interactions with other tasks and other modules. Previously unknown timing constraints can develop when changes are made. Thus, the use of microprocessors does not eliminate the necessity of a thorough design process including breakdown of requirements, selection of hardware/software modules and utilization of suitable interface design concepts.

A design has been completed for a Surface Ship Bridge Control System (SSBCS). This system was described at the 1975 Symposium by M. A. Gawitt.[1] As Mr. Gawitt stated, "The SSBCS includes a main control console operated by two men and portable maneuvering units for use on the bridge wings. The main console comprises integrated functional modules and provides the centralization of critical controls, displays, monitoring devices and communications to reduce bridge watch standing and to enhance the performance of ship conning and control functions on the bridge of a naval surface ship." The SSBCS will be the basis for a description of a design process for a complex, system incorporating a number of microprocessors.

SYSTEM DESCRIPTION

A Surface Ship Bridge Control System (SSBCS) represents a complex system requirement, best described in terms of functions. Functions can be categorized as follows:

Autonomous,
Redundant, and
Cooperative.

Autonomous functions are independent of all other functions.
Redundant functions duplicate or back-up other functions.
Cooperative functions operate in conjunction with other functions.

Each of the system modules of this SSBCS represent a separate hardware element. Except for the central controller, each is controlled by a microprocessor. The system functions are implemented in the operations of these modules, usually in co-operation with a software module in the central controller.

A simplified block diagram of this system is shown in Figure 1. A basic understanding of the functions of the system is best given by an examination of the system modules in which the functions are implemented. The hardware system modules are:

The Console/Data Interface--provides for the movement of data between other ship systems, the operator, and the other modules of the system. It also controls the illumination, indicators and read-outs of the operators console;

The Automatic Logger--creates a standard ship's log on a specialized printer. Primary data is from the console/data interface. Additional specialized data can come from the central controller;

The Display System--accepts data from the central controller and creates images in solid state memories. These memories are read-out in television raster form for presentation on the console and remote displays. As the display system commands are high-level, and the system takes care of refreshing the display, the processing load on the central controller is minimized. Five memories are included, one for a contact data list, one for operator interactions, one for charts, and two to be utilized alternatively for the collision avoidance display;

The Radar Scan Converter--provides for the scan conversion of the raw radar image to four bit gray scale television video for mixing with the collision avoidance graphics and the chart produced by the display system. The scan converter also includes a second display system which produces the normal auxiliary information of a radar display such as range rings, scale readout, compass rosette, bearing cursor and range strobe;

The Contact Tracker--provides track information to the central controller. This unit provides automatic tracking with manual acquisition. Contact position, speed and heading are reported along with track quality information; and

The Central Controller--utilizes SDEX-20, the Standard Shipboard Executive Program, as the basis of the software implementation. The software is to be written in the CMS2M language for the AN/UYK-20. The modularity of the software and its functions are illustrated by the following list of the software modules:

Data-Control
Display Management
Collision Avoidance
Directory Management
Steering Control
Piloting
Tactical Maneuvering
Radar Data Converter Interface
Tracking
NTDS Interface
Executive

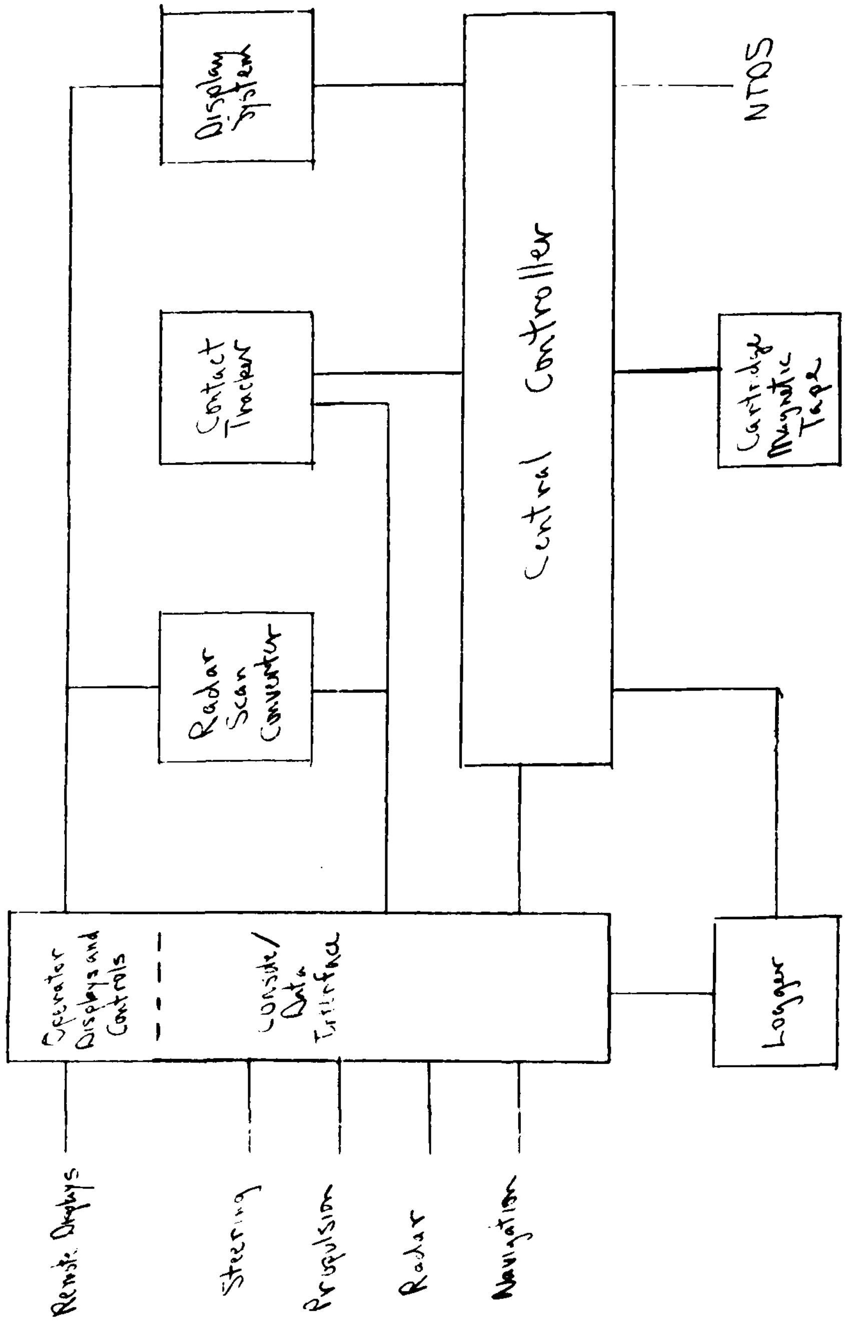

Figure 1. SSCBS Block Diagram

Peripheral Equipment Interface
Error Management and Diagnostics
Monitoring

To facilitate a low life-cycle cost profile, the system is to be constructed primarily of Standard Electronic Modules (SEMS), formally referred to as Navy Standard Hardware Program (SHP) modules. The central controller is the Navy standard mini-computer, the AN/UYK-20. The micro-processors are the Intel 8080M and the AN/UYK-30 (based on the Intel 3000 series two-bit slice CPU chips). Figure 2 shows the relative speeds of these machines and the PDP-11/40, as a familiar commercial baseline. The 8080M and the AN/UYK-30 are both implemented in SEM.

THE DESIGN PROCESS

Studies of the functions performed on the bridge of U.S. Navy combatants resulted in selection of those functions to be aided or accomplished by the system. A preliminary functional design was produced and studied by a team consisting of personnel representing system requirements, human factors, software and various hardware areas. The functions were clearly defined and logically broken-down into system requirements. The functions were then allocated to the appropriate hardware/software mix and interface requirements were determined. Interface design concepts were then selected.

THE DESIGN APPROACH

The first step in a design is to clearly characterize the functions of the system. This must include time, synchronization, interface and computational requirements. It was apparent that no central controller could satisfy all the requirements. The central controller provides a high level language, which simplifies software development and maintenance. Any data in the central controller is accessible to all software modules with no communications overhead. The central controller is the fastest processor available and the only one with hardware provision for mathematical functions. Microprocessor implemented modules provide independence, which is particularly important in the areas of functionality and timing. Parallel operation of modules is possible, unless limitations on interfacing exist and data can be secured from other modules. These considerations provide a basis for the allocation of functions for implementation in either the central controller software or in separate, microprocessor controlled modules, or both.

Functions requiring high speed and tight time dependence are best allocated to separate modules which do not have to perform other tasks. Functions of high variability are best allocated to the central controller. The variability can either be related to a multiplicity of operator options or to a level of uncertainty in the design. Where functions must be split between the central controller and a separate module, care must be taken to insure that no tight timing constraints are placed on the central controller.

The radar scan converter and the contact tracker are obvious examples of modules involving time dependence and high speed operations. In the case of the contact tracker, the results from the current radar sweep are utilized to set-up the contact tracker for the next sweep. Therefore, the estimation algorithm, a Kalman filter, which determines the next search area for each contact, was implemented in a microprocessor. The central controller can make a track add or drop request at any time, and receive track data at any time. The tracker can be requested to inform the central controller by an interrupt whenever data is available. The scan converter operates independently from the central controller.

The heaviest work load in the display system is the refreshing of the operator displays to provide for flicker-free presentations. This had to be implemented outside of the central controller. It was also decided to isolate the central controll

Processor	Throughput (Thousands of Operations per Second)
8080	21
PDP 11/40	354
AN/UYK-30	412
AN/UYK-20	512

Instruction Mix	
Branch	20%
Multiply	5%
Divide	2%
Short	73%

Figure 2. Processor Comparison

from the process of actually setting and clearing bits in the display refresh memories. A microprocessor was utilized to implement a high level command set for the display system, thus reducing the processing time required to create the display.

The multi-mode steering control provides for both automatic and aided manual control. High turn rate is provided for fire-control and torpedo avoidance modes. Finally, this system is dependent upon ship characteristics and the ship steering system. Due to these variabilities, this is a function best implemented in the central controller.

Some functions must be allocated to separate hardware modules for other reasons. This includes the automatic logger which is required to operate even when the central controller is inoperative. Another example is the console/data interface which provides too large a number of interfaces for the central controller to deal with efficiently.

INTERFACE DESIGN CONCEPTS

Once the modules are allocated, the problem of interface design remains. If the interfaces are such that the modules are time dependent upon each other, the process of debugging becomes expensive. Time dependence also causes difficulties in making changes, as a change in one module becomes more likely to affect another. Interactions between modules were selected to minimize interrupts, processor controlled inter-processor communication and unnecessary synchronization. These sorts of selections are illustrated by the following descriptions.

Information Passing Between the Console/Data Interface and the Central Controller

The information transferred between the console/data interface and the central controller can be classified as follows:

Error	(4 types)
Operator Positional	(14 types)
Alidade	(2 types)
Ship Control	(3 types)
Console Operations	(8 types)
Timing	(3 types)

The bulk of these data transfers are required due to the operation of the console by an operator. A standard approach to this sort of requirement is the use of interrupts. Interrupts require both the central controller and the microprocessor in the interface to perform processing which is time-dependent on the operations of the other machine in addition to processing which is essentially continuous.

A close examination of the use of the data to be passed shows that only error and timing information, a very small portion, need be passed at other than the 0.1 second timing of ship control operations. This allows the use of a simple, periodic data transmission, eliminating many software complexities and problems in debugging. Additionally, in order to simplify software in the microprocessor, the timing was performed there, informing the central processor by interrupt that a new cycle is due. Provision was made for the central controller to enable other interrupts if it was later found necessary to utilize that approach.

Information Passing Between the Console/Data Interface and the Remainder of the Syste

Each of the other modules of the system require information from the console/data interface. Each of these modules is computer based. Standard request-grant interfaces or a general purpose data bus through which any module could communicate with any other module could be employed. Either of these techniques provides opportunities to meet any new or unforeseen requirements with software and minimizes cable and interconnects. However, this makes all modules dependent on all other modules in timing and software, and can produce debugging nightmares. Additionally, fall back mode requirements and software complexities can be cumbersome.

An alternative approach is to make all required data directly accessible to any module that requires it. This approach can result in a lot of cabling making it unsuitable. In this particular system, the approach is acceptable since the number of bits required between most modules is small. In the case of the logger, the requirements were excessive. A multi-port memory was employed in this case. The design provides sufficiently fast response time so that timing was not a consideration. A small number of spare storage registers, accessible to all modules were included for future changes. The use of the more standard request-grant interfaces does provide for more expandability in the area of data, whereas the selected technique provides more availability in the area of microprocessor input/output time and processing time, which coupled with the elimination of interactive timing problems could provide more overally expandability.

Synchronization of the Display System and the Radar Scan Converter

As described above, at least three images, scan converted raw radar, auxiliary radar information and the collision avoidance information are combined for the main display. These will be referred to as radar, auxiliary and synthetic. Synchronization considerations must be given to the response to operator controls such as orientation (head or north up), range selection and offsets. All three images must change. This change is required to occur in a timely fashion and in such a manner that the operator is not confused by a transient image.

The central controller provides the information to the display system in the form of display commands to produce the synthetic images. A requirement to change the synthetic image can result from the passage of time, change in contact position or change in operator request. The scan converter changes auxiliary information each 0.1 second. The raw radar image is produced continually, a full image drawn over a period of three or four seconds, the radar scan time. New information simply replaces old except that the entire display is erased when change is required by operator control. The scan converter must function without the central controller or the display system to provide a high reliability fall-back mode of operation.

One can conceive of schemes for synchronizing the synthetic and auxiliary information, with the erase of the raw radar. Schemes of this nature would result in the operations of the central controller, the scan converter, the display system and the console/data interface becoming mutually dependent. The fall-back mode would require an additional layer of software and controls.

The approach taken is to allow each image to change in its own timing. This results in independence of each of the associated modules. The presented image will have disagreeing synthetic and auxiliary information for no longer than 0.1 seconds, starting no longer than 0.1 seconds after the operator's request. After this, these two images will be correct. The radar image will be completely erased upon the operator request, and the new image produced as the scan progresses. This performance was evaluated and found to satisfy requirements.

CONCLUSIONS

A complex system often includes a multiplicity of hardware components (modules) interacting to perform the various functions of the system. The benefits of constructing such a system in a modular fashion include maintainability and simplified development. If the interactions between the modules of a system are complex, the modules become interdependent. This results in the loss of the benefits of modularity as system design and debugging become more expensive and the implementation of future changes becomes more complex.

The functions of the system should be clearly defined and the requirements understood. To insure true modularity, the allocation of functions between the central controller and the separate modules should be accomplished based on considerations related to speed, time-dependence, variability, interface and fall-back requirements. Functions requiring high speed and tight timing are best allocated to separate modules.

Complex interactions between modules can result from poor allocation of functions and can represent too narrow an interpretation of requirements or an over reaction to requirements. Unavoidable interactions can be simplified based on interface design concepts featuring:

Elimination of unnecessary interrupts to a processor,

Elimination of processor controlled inter-processor communication, and

Elimination of unnecessary synchronization.

These concepts provide a methodology for aspects of the detailed system design as well as a basis for stating system requirements to insure modularity.

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MICROPROCESSOR SOFTWARE - A STRUCTURED APPROACH TO CONTROL & SURVEILLANCE SOFTWARE FOR MARINE APPLICATIONS

by G J Hindmarsh Vosper Thornycroft (UK) Ltd

ABSTRACT

The introduction of computers, in the form of microprocessors, into new areas of marine application not only brings many potential advantages but also a number of pitfalls. The greatest area of danger is almost certainly in the software which goes with computer based systems. Can the software be made sufficiently flexible to use large portions on more than one application? Can a high level of quality assurance be obtained? Most of all can the software be adequately and easily maintained during its operational life? On these questions and any solutions the success or failure of computer based systems stands or falls. This is particularly true of marine applications where a computer based system may have to be operated for anything up to 25 years.

The paper describes the Vosper Thornycroft's D77 system approach to software. The fundamental concept employed is that of modularity. This is common practise these days but the D77 system goes much further. It uses functional modules in a structured design such that inter-dependance of modules only occurs at the highest level possible. The paper discusses the effect of this approach on software preparation, standardisation, quality assurance, setting to work, documentation and customer support.

SUMMARY

Like many other companies engaged in the field of marine control and surveillance systems, Vosper Thornycroft (UK) Ltd. Controls Division are continually seeking to reap the benefit of advancing technology to further improve the performance and reliability of its products. The aspect of this subject chosen for this paper is that of the introduction of computers, in the form of microprocessors, into new marine applications.

This introduction brings many potential advantages, but we believe, on the basis of the extensive experience of our engineers over many years in computer systems and marine automation, that there are a number of serious pitfalls.

The greatest area of danger is almost certainly in the software, which goes with computer based systems. Can the software be produced to meet the same high standards of reliability achieved by present day hardware? Can the software be adequately controlled during the design and production process? Most of all, can the software be adequately and easily maintained during its operational life which might be anything up to 25 years? The answers to these questions will decide the success or failure of computer based systems.

Figure 1 summarises the benefit of the D77 approach. Briefly, the message is that by positive effort in the early definition of the customers' requirements and by designing the computer software according to certain well defined principles, tremendous benefits can be obtained in the testing and post acceptance periods.

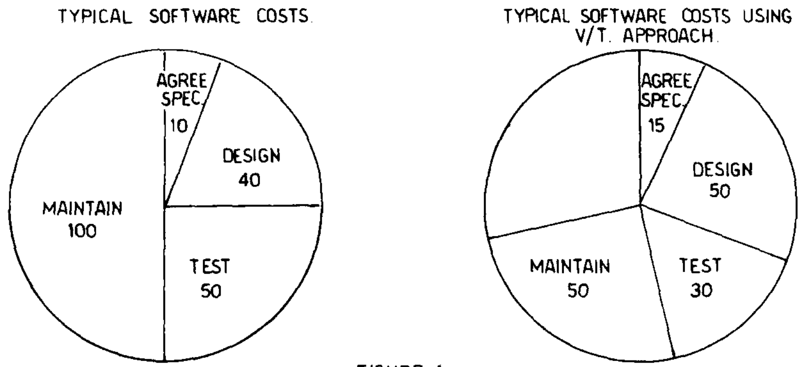


FIGURE 1.

INTRODUCTION

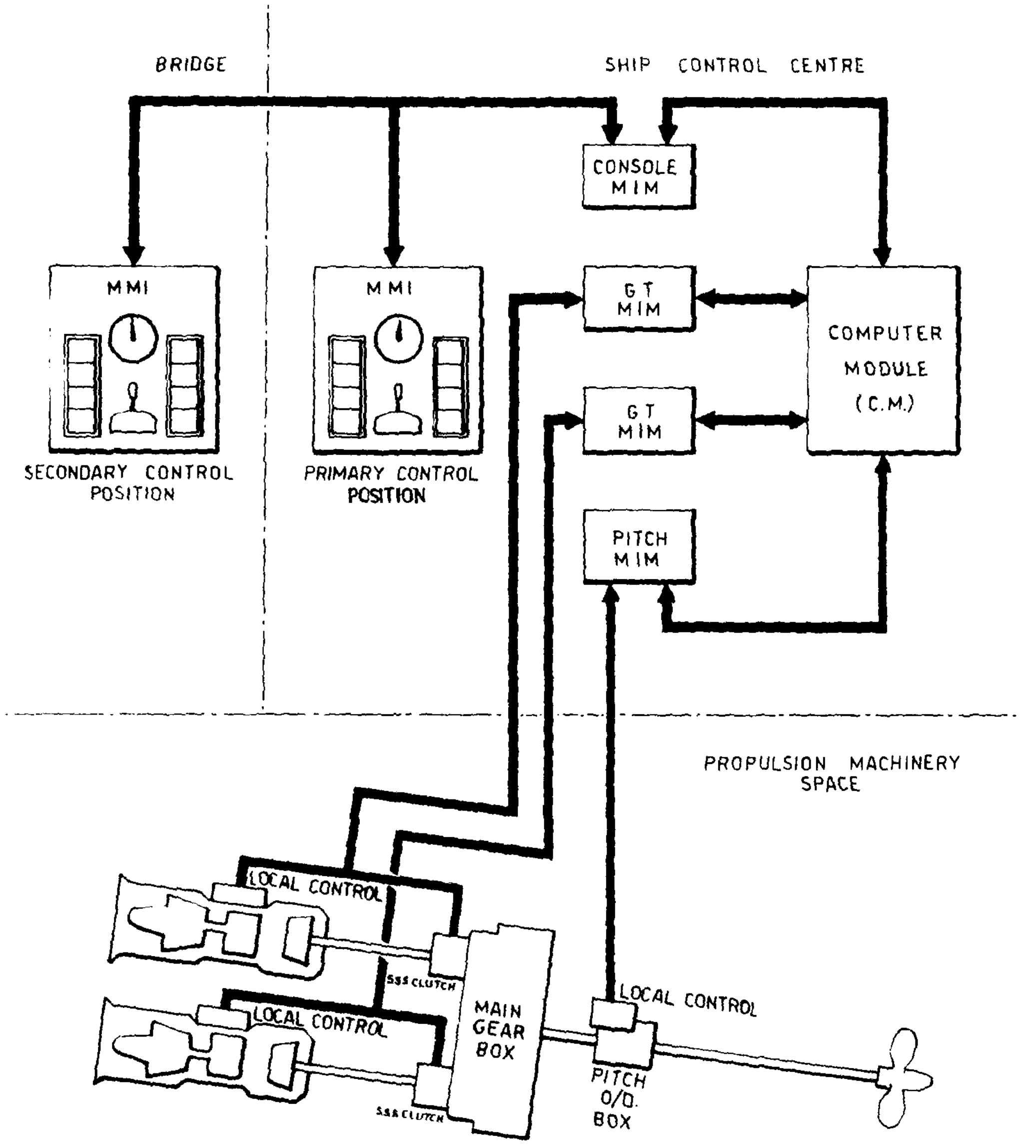
The use of electronics in control and surveillance equipment is a fairly recent innovation by marine standards. However with the increasing sophistication of machinery and the ever growing demands of the ships operators the control and surveillance systems have well and truly emerged at the high technology end of ships equipment. The generation of equipment in use at the moment has shown many advantages over its predecessors but it has also grown more and more expensive to the point where much more flexible equipment has become vital to maintain the economic viability o' complex systems. Hence the arrival of computer based systems.

The Vosper Thornycroft contribution to the new generation of computer based systems is known as "the D77 system". Unlike many other systems, which have simply evolved out of research projects, the D77 system has been designed from the start with the specific aims both of supplying the required higher level of environmental capabilities and of minimising the ever increasing costs of purchasing and owning this type of equipment.

The D77 is a microprocessor based control and monitoring system designed for maximum flexibility with the overriding constraint that it should meet the requirements of naval applications (i.e. a severe environment including large doses of nuclear radiation). The hardware is divided into two basic types of module; the Computer Module (CM) and the Machinery Interface Module (MIM). Generally, one MIM is used to interface with each physically separate item of plant (Machinery or console). Each MIM may have its own CM or several MIM's may be connected, via a bus, to one CM which in turn may be duplicated for high integrity applications. Where several CM's are used in a system they may be interconnected by serial links. Figure 2 shows the modules used in a centralised, low cost system.

Figure 2

CENTRALISED APPLICATION OF D77 TO A COGAG CONFIGURATION



It can be seen that this hardware may readily be used in a large variety of applications; centralised or distributed, high or very high integrity, simple, low cost or complex higher cost systems. One great advantage of this flexibility is that the system integrity philosophy adopted for the machinery may be continued through to the control system thus eliminating potential incompatibilities.

The advantages gained from computer based systems are primarily derived from the fact that new functions are implemented by redesigned software rather than redesigned hardware. Hence the economics of the approach hinge around the computer software which is the main subject of this paper.

THE PROBLEM AREAS

Marine control and surveillance equipment manufacturers operate in a difficult environment where design costs are high due to the complexity of equipment and yet production quantities are low (sometimes even one-off). This means that design costs are a very significant proportion of the overall cost. Thus to keep costs down design effort must be minimised for each application. It has usually been reasoned that transferring the redesign task for new applications from hardware to software will result in a significant improvement. Whilst this can be true there are many pitfalls for the unwary. The potential problems fall into two categories.

The first category contains those problems arising during the design and production phases of the contract.

The second contains those problems during the post acceptance period (which can be anything up to twenty five years long).

Problems during Design and Production

The problems which arise in the design and production of software are common to all software applications. Thus experience from other fields, such as weapons software, is directly applicable.

Typical problems are:-

(i) Design changes during the project, usually resulting from using an inadequate specification, causing redesign of the software with consequent delays.

(ii) An underestimation (often a very large one) of the time required to test and set to work the software.

(iii) Overrunning the originally estimated computer timing and memory allocation causing a redesign at quite a late stage in the project.

(iv) Loss of staff and lack of standards necessitating the re-writing of a section of software because no one understands the original.

To take an example suppose that the software for a machinery control system is prepared using calculated propeller performance information. When the actual propeller data arrives it may let us say, indicate the need for more complex fuel/pitch schedules and an automatic pitch fining system.

This would inevitably result in a requirement for more memory and processor power. If this were unavailable then in a poorly designed program a complete redesign might be necessary. In a program with a number of self contained modules the introduction of another computer would be easier. Ideally, of course, adequate margins should have been left for this contingency.

MAINTENANCE PHILOSOPHY

Introduction

The most sophisticated of systems is inadequate if

a) It cannot be maintained by normal naval technicians

b) It spends long periods under maintenance and repair (long down-times)

c) It costs a fortune for its upkeep.

Fortunately, routine maintenance can be reduced almost to that needed for the home T.V. set (i.e. check that it's still there). When things go wrong, however, the technician needs as much help as possible in quickly identifying faults and subsequently rectifying them.

Routine Maintenance

The underlying theme here is "performance checking", i.e. if the system is working correctly then leave it alone. Two types of tests are incorporated:

a) Continuous automatic operational monitoring to detect the development of faults.

b) Machinery simulation tests to allow the operator/maintainer to exercise the control electronics.

Programmes held by the control processors carry out these functions.

How to achieve Low Down Times on Board Ship

a) Use modular electronic building blocks

b) Repair the system by module replacement

c) Ensure that there are an adequate number of test points (and that they are accessible) to simplify setting to work procedures

d) Use a built in test (BIT) system to identify fault down to module level.

Keeping Costs Down

a) Minimise the number of module types (spares support costs)

b) Incorporate comprehensive and dependable test facilities (maintainer Costs)

c) Use the control equipment to provide BIT functions (equipment costs).

Built in Test (BIT)

The test system is an intrinsic part of the propulsion control system, and is designed to meet the following requirements.

a) The BIT equipment uses a minimum of additional hardware.

b) It does not lead to a lower system availability.

It was found that:

a) In no case was it necessary to develop more than two module types.

b) Overall development timescales were significantly reduced.

c) The confidence factor in the system design was very much increased.

The system was also assessed against the requirements of vessel (b) using a non-distributed control system. Only three additional module types needed to be developed.

Limitations and Disadvantages

a) The total number of modules needed for a specific application is not optimum.

b) More electronic hardware is normally needed for a distributed control system than for a non-distributed one.

c) Some standardisation of plant analogue signals handled by the system is needed in order to minimise the number of module types.

CENTRAL PROCESSING UNIT

General

The system design is such that it does not depend on the use of a specific type of micro-processor. The central processing unit (CPU) is a general purpose computer on a p.c.b., and contains:

a) The microprocessor
b) Memory (store) devices
c) Special purpose devices

Memory

The CPU uses semiconductor memory only, and contains:

a) Read Only Memory (R.O.M.) - a non-volatile store for programme instructions and fixed data.

b) Read-write or Random Access Memory (R.A.M.) - a volatile store for variable data.

c) Non volatile R.A.M. - for Semi permanent instructions and data, such as alarm limits, control laws, etc.

Special Features

The CPU also contains:

a) A real time clock and watchdog timer
b) Hardware timer facilities
c) Direct memory access features for high speed data transfer
d) A simple interrupt structure
e) A serial communication channel (to operate with either a teletype or Visual Display Unit (VDU)).

Where performance and size constraints have been significant the "standard" modules have tended to become non-standard fairly rapidly.

However, a modular system based on the microcomputer has outstanding flexibility because control laws, signal processing, sequencing requirements etc. are not a function of hardware.

Implementing the Modular System in Hardware

Even though the U.S. Navy has a preference for Standard Electronic Modules, and despite the wider use of hybrid electronic devices, the printed circuit board still has many advantages. Therefore the propulsion control system electronics uses printed circuit board modules as building blocks. The key factors in defining the modules are shown in Fig. 2.

Figs. 3 and 4 depict the physical and functional solutions for the System Control Unit and a Gas Turbine Control unit for a COGAG system.

Capacity and Expendability

To allow for system change and expansion:

a) The central processing unit (CPU) module is designed to handle a much greater volume of work than that which actually exists at any point in the system.

b) On Input/Output modules a percentage of channels is left spare, and space is left in the rack units to fit additional modules.

c) Careful consideration has been given to the provision of stabilised power supplies for the control electronics.

Adaptability

The system was initially designed for a COGAG fit, and used 10 different module types. It was then assessed against:

	Type Fit	Type Vessel	Propulsion Units	No. Shafts	Propeller System	Clutches
a)	CODOG	Corvette	One G.T. Two Diesels	2	CPP	1 SSS 2 Fluid Coupling
b)	CODOG	Corvette	One G.T. One Diesel	2	CPP	1 SSS 1 Pneumatic
c)	CODOG	Frigate	2 G.T. 2 Diesel	2	CPP	2 SSS 2 FC
d)	COGAG	Frigate	4 G.T.	2	FPP + revers-ing gearbox	4 SSS

iii) "Local", at each item of plant.

All manually instigated Start/Stop sequences are normally controlled from the SCC.

e) Information flow between the various sub-systems is defined as

   i) Control (all control signals and plant information required for normal control of the propulsion machinery).

   ii) Surveillance (all other information from the propulsion machinery).

   iii) Electric Manual (minimum essential information needed for remote manual control of the machinery).

f) The control information is transmitted on a serial digital data highway, (Fig. 1). This conforms to MIL STD 1553B and is fully duplicated.

g) The surveillance also travels over a similar highway (Fig. 1).

h) Electrical manual control uses dedicated hard wiring (Fig. 1).

j) The control system is based on the use of microcomputers.

k) The electronic building blocks are printed circuit board modules, each with defined functions. These enable different systems to be configured (CODOG, COGAG, etc.) with minimum design changes.

l) The system incorporates full self test facilities.

m) Power for the electronics is derived from the ship's main A.C. supply via duplicated power units, which provide a D.C. supply with battery support.

HOW FLEXIBILITY IS ACHIEVED

Introduction

The electronic system is designed to accept changes in:

a) Configuration and application
b) Modes of operation
c) Control algorithms and performance specifications
d) Number and type of plant input/output signals.

The Modular Approach

A special to purpose design will not satisfy the requirements, and the usual solution is to use standard hardware building blocks, or "modules".

Past experience shows that most systems need special modules in addition to the "standard" modules. In propulsion control systems where standard modules (using conventional analogue and digital (non computer techniques)) have been used:

a) The control laws have tended to be simple
b) The physical size of the electronics package has been large.

b) Data highway systems, correctly designed and installed, are much less likely than conventionally wired systems to cause plant malfunctions under battle damage and other conditions.

c) The ability to "add on" and modify systems without major changes to the ship's wiring is a significant factor.

d) Installation and commissioning costs and timescales can be significantly reduced by using a data highway system. The costs of planning and drawing cable routes, preparation of cable schedules, etc. are reduced.

Emergency Fall-back Mode

To ensure safe operation of the propulsion system under fault conditions (whilst the local control stations are being manned) a remote manual control system is fitted. This allows direct electrical control of critical plant items. To preserve the propulsion system integrity it does not use the normal data highway, and is hard-wired (for cost effectiveness).

Selection of MIL STD 1553B

a) Our own work has shown that command-response methods of data multiplexing are easy and simple to implement.

b) Noise interference trials which we carried out on a modern warship showed that the performance of a high quality cable system was extremely satisfactory.

c) A recent study in the aerospace industry (3) for data multiplexing has shown that different solutions do satisfy the same system requirements. We consider that the use of a technically sound and acceptable standard system is of major importance.

d) MIL STD 1553 will in future be widely used in the U.S.A., and the U.K. GEC-Marconi Electronics are currently carrying out development work on a 1553B system for the Ministry of Defence.

e) As part of a recent study for the U.K. Ministry of Defence we assessed the use of a 1553B system in a propulsion control system, and found that technically the system was quite satisfactory.

SYSTEM ORGANISATION

The general organisation (Fig. 1) is as follows:-

a) The complete system is split into a number of clearly defined sub-systems.

b) Each sub-system has a set of control electronics which are physically located at the sub-system. Co-ordination of overall system functions is carried out by the system control unit.

c) The main control station for the system is the ship's control centre (SCC).

d) The control modes of the propulsion machinery are:

i) "Automatic", from remote stations.

ii) "Electric Manual", from the SCC (non automatic push-button control of the machinery).

SYSTEM CONCEPTS

General

The proposed control system uses distributed control techniques, with plant control being carried out by microcomputers and the plants being linked together by a digital data highway system conforming to MIL STD 1553B (2). Remote emergency control is carried out using an electric manual control system.

Distributed Control Concept

Distributed control techniques devolve control and decision making down to individual plant level because:

a) If the plant control electronics are damaged due to battle action, then the plant is likely to be damaged. This lessens the chance that the electronics may be destroyed and yet the plant itself remains functional.

b) When faults do occur in the plant electronics the faulty section can be isolated easily and quickly and the fault does not propagate through the complete control system.

c) The AVAILABILITY of the propulsion system is greater than with existing systems because we can run under automatic control in a degraded mode with plant or control system faults present.

d) Installation, commissioning and sea trials can be significantly speeded up by developing the plant and its control equipment as a single entity.

The Microcomputer

A microcomputer system has the following features:

a) Changes to the operating requirements during development and in-service can be easily accommodated.

b) The basic system is able to fit a variety of vessels without major hardware design changes.

c) The same hardware can be used in other applications and thus overall costs are reduced.

d) The number of different types of electronic modules needed is relatively small, again keeping costs down.

e) Very much improved testing methods are implemented relatively easily.

f) For more advanced systems overall availability can be improved by using redundancy/reconfiguration techniques.

The Data Highway

a) All sub-systems must be as independent as possible. The data highway enables quick and simple disconnection of individual sub-systems to allow servicing/maintenance/fault finding etc. on the sub-system without disturbing the rest of the system.

PROPULSION CONTROL SYSTEM REQUIREMENTS

General

The requirements for the propulsion control system are fundamentally the same as for all marine control systems, which were widely discussed at the 4th SHIP CONTROL SYSTEMS SYMPOSIUM (1).

They are:-

a) High availability
b) Minimum susceptibility to battle damage
c) High performance
d) Minimum through life costs
e) Optimisation of manning.

High Availability

The availability of the system is defined as

$$\frac{MTBF}{MTBF+MTTR}$$

The requirement for high availability means that not only reliability but also maintainability must be given high priority during system design.

Minimum Susceptibility to Battle Damage

A warship is designed to fight. If the propulsion control system fails in the event of minor action damage the effects on the performance of the vessel as a fighting unit is unacceptable.

High Performance

Modern vessels demand increasingly improved performance in terms of manoeuvrability, acceleration/deceleration, fuel consumption and controllability. These, in turn, tend to lead to lower safety margins.

Minimum Through Life Costs

The largest single cost in the life of an equipment is that required to sustain it in service. The second largest item is the cost of installing and commissioning the system together with provision of the appropriate documentation. These factors will increase the demand for true standardisation, commonality, and adaptability of the electronic control equipment.

Optimisation of Manning

The manning criteria for Naval vessels are outside the scope of this paper. However it is a fact of life that though increased automation leads to a reduction in watchkeeping staff manning, it can (unfortunately) increase the maintenance staff numbers. It is unlikely that the next generation of propulsion control systems will reduce the number of operators required (when compared with the latest types of warships), therefore the emphasis will be placed on reducing maintenance requirements.

PROPULSION CONTROL SYSTEM FOR THE 1980's

by Jim E. Cooling

Marconi Radar Systems Ltd., Control and Simulation Division

ABSTRACT

This paper, which is the result of in-house studies by Marconi Radar Systems Limited, defines a future propulsion control system based on the use of a distributed control scheme. Controlling functions are organised by micro-computers and communication between control units is by a data multiplexed highway system. Hardware and software aspects of the system are discussed, including the following topics:

a) Distributed Control Concepts

b) Microcomputers - Features, advantages, and processor organisation

c) Digital data systems - with particular reference to MIL. STD. 1553B

d) Flexibility - Capacity, expandibility, adaptability, limitations

e) Maintainability - Fault diagnosis, testing (including BIT), repair philosophy, maintainer displays

f) Software Documentation - Design, programming techniques and language, modifications

b) Electromagnetic compatibility requirements

INTRODUCTION

We are at the beginning of an exciting era of radical change in the design of ships propulsion control systems, which has been brought about by two major factors.

Firstly, the 3rd revolution in microelectronics, the microcomputer, is now well and truly established. By using the capability of these devices we can incorporate intelligent, adaptive and highly complex control functions which significantly improve performance and availability (at no extra cost).

Secondly, digital data transmission has been accepted as a realistic technique for shipboard use. Using this in place of conventional wiring methods will have a major effect on the vulnerability and survivability of the control system under battle damage conditions. We will also see considerable changes in development, draughting, installation and commissioning techniques as a result of this.

This paper defines the propulsion system requirements, the proposed solution to these requirements using a distributed control system based on microcomputers linked together by digital data highways, the justification for this solution, and some consequential effects of the control scheme.

As for the second problem the customer's involvement throughout the design process, with contractually defined stages at the completion of specific phases of design definition, has, and continues to be the most important feature of Vosper Control system contracts.

This aspect of Vospers' contractual approach is called SPS, or System Performance Specification. It is, we believe, quite unique and represents an understanding and agreement with the customer regarding the controls specification which recognises the central role played by the control system in terms of the performance and reliability of the total machinery package and the ship.

In short, Vospers use of the SPS approach:

(i) provides the most effective base for data management

(ii) is the most efficient way of representing the overall system

(iii) involves the use of simulation techniques which describe overall system responses in terms understood by all, which is vital to promote total understanding

(iv) very significantly reduces the potential problems which may arise at the commissioning phase

CONCLUSION

This paper has attempted to identify some of the pitfalls which lie waiting for the unwary or inexperienced software designers. It has also presented one approach to overcoming the problems. With the well defined and disciplined approach described in this paper Vosper Thornycroft are confident that a system involving software can be relied upon, can be controlled and thus can be profitable.

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Design/Production Procedures for Quality Assurance

The control of design and production procedures is very well established in the hardware areas. However many of the procedures are very firmly biased around the design and production of sophisticated hardware and do not at first sight seem applicable to software. There is thus a very strong temptation to let the software engineers implement their own ideas. The results of this are usually disastrous and it is only the extreme flexibility of software which has saved the day on many projects. A closer look at the hardware procedures reveals that many of them are applicable to software, others are applicable with minor changes and the amount of new procedures necessary is relatively small. The D77 approach uses firm controls in four areas:

Software Design Standards. In addition to the software design techniques discussed earlier a number of design standards have been specified for the preparation of D77 software. The aim of the design standards is to ensure a high level of understandability and maintainability. The standards cover the production of program specifications, Flowcharts and program code.

Software Documentation. The D77 software production process is designed to be auto-documenting. Each level of design results in documentation which is appropriate to its level of understanding. Documentation is produced as the design progresses so that it provides "milestones" by which management can monitor and control the software production process.

Testing Procedures. In the D77 approach a big accent is put upon the testing procedures. The techniques adopted to ensure a reliable product are:

(i) The specifications resulting from the various design levels or processes have to be checked and approved before the design is allowed to progress.

(ii) A "Bottom up" testing approach is used to test the programs. This involves using a standard test program which enables sub modules to be exercised with test cases. The sub modules are then integrated into modules and the modules tested. Finally the modules are integrated into the system and the system is tested against a system test specification.

(iii) Software testing is not carried out by the designer. It is handed over to a software test engineer as soon as it compiles correctly. The software test engineer has meanwhile prepared test cases from the same program specification used to prepare the program.

(iv) Test cases are devised to cover a wide selection of input conditions including all boundary conditions and to ensure each branch in the program is exercised at least once.

Modification Control. Modification procedures are applied to any changes which affect any program or item of documentation which has already passed through its checking, or testing, and approval stage. The modification procedure invoked is almost identical to the existing hardware practise of raising change notes which have to be authorised and recorded.

Customer Involvement

Two of the common mistakes in software projects are a failure to understand the user's environment and a failure to involve the end user of the product in the decision making process. We at Vosper Thornycroft Controls Division are in a unique position to avoid the first problem because of our very close ties with the Vosper Thornycroft Shipbuilding Division.

TOP DOWN DESIGN PROCESS

SPECIFICATIONS

<u>TOP LEVEL</u> (S/W STRUCTURE DESIGN)

1. Identifies major software Modules required e.g.
   GT Module, CPP Module, etc.
2. Allocates computer resources

SOFTWARE FUNCTIONAL SPECIFICATION

<u>2ND LEVEL</u> (MODULE DESIGN)

Identifies sub modules required e.g. GT Start GT Stop etc.

MODULE SPECIFICATIONS

<u>3RD LEVEL</u> (SUB MODULE DESIGN)

Detailed Analysis and Design of each Sub Module

SUB MODULE SPECIFICATIONS

<u>4TH LEVEL</u> (CODING)

Programming of sub modules

CODE

-- END OF DESIGN

TESTING PROCESS

FIG. 4

meet all the objectives without any real conflicts. The more important of the techniques are:

Top Down Design. One of the worst problems to face when designing sophisticated equipment or indeed, trying to understand another person's design, is the complexity. Perhaps the most successful approach to understanding a complex problem is to stratify the problem into levels of understanding. This is the principle of top down design. It can, of course be applied to both hardware and software but as this paper is primarily about software we will limit the discussions to that. The D77 design approach is usually restricted to 4 levels but this is entirely a function of the complexity of the task. The levels are shown in Fig. 4.

Whilst the main advantage of this approach is that of reducing the problem complexity there are two other important advantages.

(i) Provided each level of design is appropriately documented and controlled it does form a very effective project control and quality assurance tool. This is discussed further in 3.3.

(ii) The approach is very suitable for the techniques of functional modularity and structured programming.

Functional Modularity. Functional Modularity is almost self explanatory. In the case of a machinery control system the software is split into a Gas Turbine module, a CPP module,etc. and each module is split into submodules such as a Start Sub-module, a Stop Sub-module, a Control Sub-module, a Barring motor Sub-module and so on. The advantages are four-fold. Firstly the software is easier to test. Secondly the software is easier to understand. Thirdly it will be more suitable for re-use on subsequent applications and fourthly it will be easier to modify.

One important feature of the D77 modules and sub-modules is that they are completely independent about a given level of design, dependence only occurring at higher levels, e.g. Sub-modules are only linked by a module executive and modules only by a system executive. This significantly adds to the aforementioned advantages.

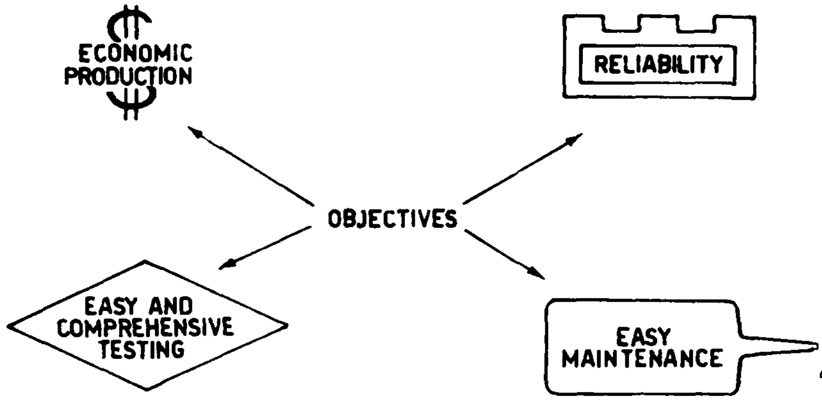
Structured Programming. Structured programming is more of an approach to programming than a formal programming technique. It is an attempt to write programs with the intent of communicating with people rather than machines. This is achieved by splitting the program into easily understood segments, by making the program flow from top to bottom, i.e. avoiding the use of branch statements, and by minimising the complexity of the code. Structured programming readily mixes with functional modularity and top down design but it has one complication regarding its use with microprocessor based systems. It is very difficult to achieve the aims of structured programming in anything other than a high level programming language.

The Programming Language

The programming language used has a considerable effect on software reliability and "understandability". In fact from these aspects the case against assembler languages is virtually watertight. However, microprocessors are not yet as powerful as other computers and the 100% use of a high level language is often impossible. The D77 approach is to use a library of efficient, assembler programmed subroutines, which do not change from application to application, and to make use of CORAL 66 in the application dependent part of the program.

THE D77 APPROACH

The D77 approach to avoiding the potential problems is based on four main objectives, thus:



An analysis of the best ways of achieving these objectives reveals five identifiable areas where control is possible.

(i) The quality of personnel used

(ii) The design techniques employed

(iii) The programming language used

(iv) The design procedures with particular regard to quality assurance

(v) Customer involvement

The Personnel Policy

The differences between an experienced software designer and an inexperienced software designer are always vastly underrated for some strange reason. This is especially true when it comes to writing high integrity software for complex applications. It is part of the D77 approach that software designers well experienced in the techniques of designing highly reliable programs are used.

The Design Techniques

The design techniques employed in preparing software have repercussions on all four objectives mentioned earlier. Firstly, there are a number of well established techniques for designing reliable software. Secondly, by careful selection of programming standards and techniques it is possible to produce software which can be easily modified. Thirdly, one can considerably simplify the task of setting to work by the correct choice of design and fourthly the correct design approach can minimise the redesign time for subsequent applications thus improving the economics.

Fortunately it has been possible to choose a set of design techniques which

If the originator of the relevant part of the software was unavailable then without very good standards and without good, up-to-date documentation it is likely to be quicker, and would certainly result in a more reliable product, if this software were completely re-written.

Finally, in a poorly designed software system such a change would have repercussions in other areas (eg. storage allocation) which is likely to require a complete retest of all of the software - a very time consuming process. It can be seen then that such a change could have grave repercussions on project time-scales. Section 3 describes how the D77 approach overcomes these problems.

Problems during the in Service Period (Software Maintenance)

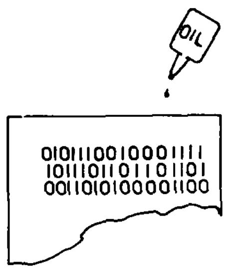
The potential pitfalls with software do not end when the acceptance tests are successfully completed and the product is handed over. In fact on many projects this is where the worst headaches begin. For example how many people are aware of huge amounts of money being spent on maintaining what might be termed military defence systems software. Probably no one knows the true figure but it almost certainly runs into hundreds of millions of dollars per annum in the US alone[1].

Why is Software Maintenance necessary?

(i) Operational errors undiscovered until well into operational life.

(ii) System requirements changing as a result of operational experience.

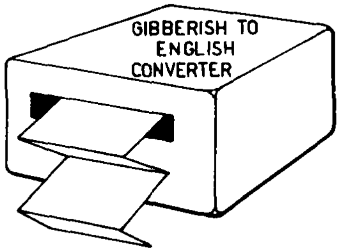
(iii) Machinery changes during refit.



What are the Major Problems?

(i) The software will have to be maintained by other than the original designers, which presents the problem of design interpretation.

(ii) Modifications made in one area can easily ripple through to other areas.



c) It is able to distinguish between true faults and transient errors.

d) It contains self validation checks.

e) It is simple to use, and the results are easily and unambiguously interpreted.

Fault Finding

The tests carried out are defined either as "on-line" (Machinery in full automatic control) or "off-line" (machinery stopped or in local control), and the use of these is shown in Fig. 5. Faults are identified as follows:-

a) System functional testing is carried out using simple disturbance (perturbation) methods, with go/no go type decisions.

b) Processor checks are carried out by performing defined mathematical operations and comparing the result against a stored value.

c) The programme is analysed for corruption by using a technique known as "checksum".

d) Plant interface modules are checked out using specific on-module test circuitry.

TUNING AND ADJUSTMENTS

The Problem

There will be a need to change control laws, alarm limits, etc., as a result of development work, sea trials and specific operating conditions. Where control laws and functions are complex, and where numerous alarm/warning conditions are monitored, the conventional methods (i.e. using adjustable potentiometers, changing fixed electronic components to "characterise" circuits) leave much to be desired.

The Solution

The method used here is to hold these factors in an electrically alterable read-write store, using non-volatile semiconductor memory devices. The operator/maintainer accesses the store and makes the changes using a special purpose unit (which contains a teletype, controls, and alpha-numeric displays). This allows the operator to change system control parameters, subject to inbuilt safety factors.

ELECTROMAGNETIC PERFORMANCE

Introduction

The problem of Electromagnetic Interference can be divided into:

a) Generated Radio Frequency interference (RFI), where the electronics of the propulsion system causes interference with communications equipment.

b) Electrical interference and noise from external sources which cause faulty operation of the control system.

Generated R.F.I.

This presents a difficult problem because the magnitude of the interference cannot normally be predicted from theoretical studies. Various features are designed in to contain it, i.e. use of filters to reduce conducted interference, enclosure materials and shields to absorb radiated energy, components with defined R.F.I. absorption properties, and the correct type of cabling and cable routing.

Received Interference and Noise

The received interference is conveniently categorised as:

a) that generated by communcations and radar equipments:

b) power supply transients.

c) voltage/current transients on the input/output signal lines generated by switching of electrical equipment.

Work previously carried out (5) has indicated that for below-decks equipment interference of type (a) does not appear to be a major problem (though careful routing of the data highway may be necessary). Power supply transients are a nuisance, but methods for dealing with these are well established.

The effects of transients on the signal lines in the plant are likely to be the greater problem and to minimise this problem:

a) fit transient suppression/protection networks on the lines.

b) provide electrical isolation between the input/output lines and the internal circuitry of the control system electronics where applicable.

c) consider carefully screening, bonding and earthing arrangements.

d) transmit plant analogue D.C. signals at a high level.

e) measure analogue signals (especially low level ones) differentially, in order to reduce common mode noise effects.

SOFTWARE DESIGN AND DOCUMENTATION

General

A major advantage in using a microcomputer is that once a design has been proved the control equipment can then be treated as hardware only. The operator/maintainer does not need to have any knowledge of the programme or programming languages/techniques (tuning or adjustments can be carried out using a very limited set of clear instructions). System repair is carried out by replacing faulty modules.

However, from the design and development point of view, the design rules and the relevant documentation need to be defined, and at present this is a very contentious subject.

Design Objectives

The objectives are to produce programmes which are:

a) Error free - this is the definition of a "reliable" programme.

b) Clear - in order that the programmes can be understood by others.

c) Cost effective - both in terms of the initial costs and any subsequent in service support.

d) Efficient - in terms of store requirements, programme speed, and precision of results.

e) Portable - the language used and the method of construction of the programmes must allow for easy installation in other microcomputer systems.

f) Modifiable - modifications to the programme to cope with system performance changes should be easy to implement.

Design Methods

Structured programming is the preferred design tool because we believe that software reliability cannot be proved by testing, and therefore techniques must be used which minimise the possibility of errors getting into the programme in the first place.

In general the principles of structured programming (4) are:

a) Programmes are developed from the "top down", i.e. initially a simple description of the overall process is specified, and then the problem is gradually decomposed into lower levels (this procedure is defined as "modularisation").

b) The complete programme is organised into series of intermediate system of programmes, or "modules".

c) The syntax (programme constructional rules) allows only limited control structures.

d) The size of each programme module is limited.

Features of Structured Programming

The advantage of structured programming are:

a) The design is logical and orderly, and the problem of programme integration which occur in bottom-up design are virtually eliminated.

b) The relatively small size of each module minimises the number of mistakes made in the initial programmes, which in turn reduces the debugging time.

c) The independent nature of the modules allows for independent (and hence easier) testing of each module.

d) The <u>overall</u> development time is reduced.

e) The modular structure makes it easier to introduce changes and additions to the overall programme.

f) The resulting software is highly reliable.

The disadvantages are:

a) The resulting programme is larger than it needs to be, and hence the required memory size is increased.

b) The overall operation of the control process is slower.

Software Documentation

The documentation required for the system software development comprises:

a) Programme coding
b) Test specifications
c) Design specification
d) Performance specification.

Fig. 6 defines the organisation of these documents to enable design of a complex system to be carried out with a minimum of sleepless nights.

CONCLUSIONS

The system outlined here is a sophisticated type of propulsion control equipment for a warship. It uses only a small number of different types of electronic modules, and derives its flexibility from the use of software techniques. The same basic hardware can be used in different machinery configurations, and yet it is also a cost effective solution for simpler control schemes.

The electronic technology and devices are currently available, and have been proven outside of the naval marine. The state of the art is such that this technology can take us through to the year 2000 without creating obsolescence problems.

The microcomputer based systems, together with the use of digital data transmission methods, should lead to improvements in performance, cost, system availability, and maintainer levels on board ship. If it does not we have wasted our time (and money) developing it.

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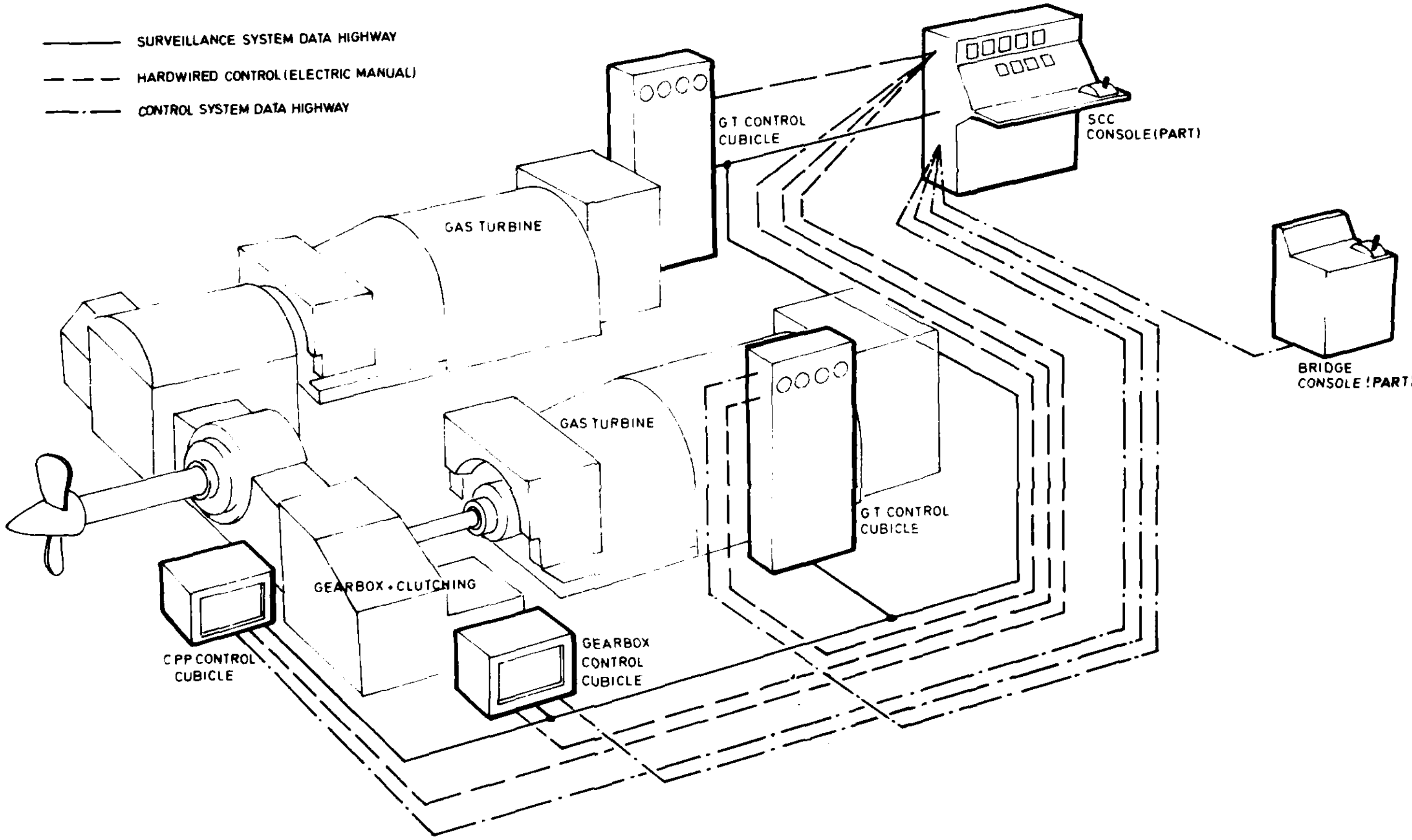
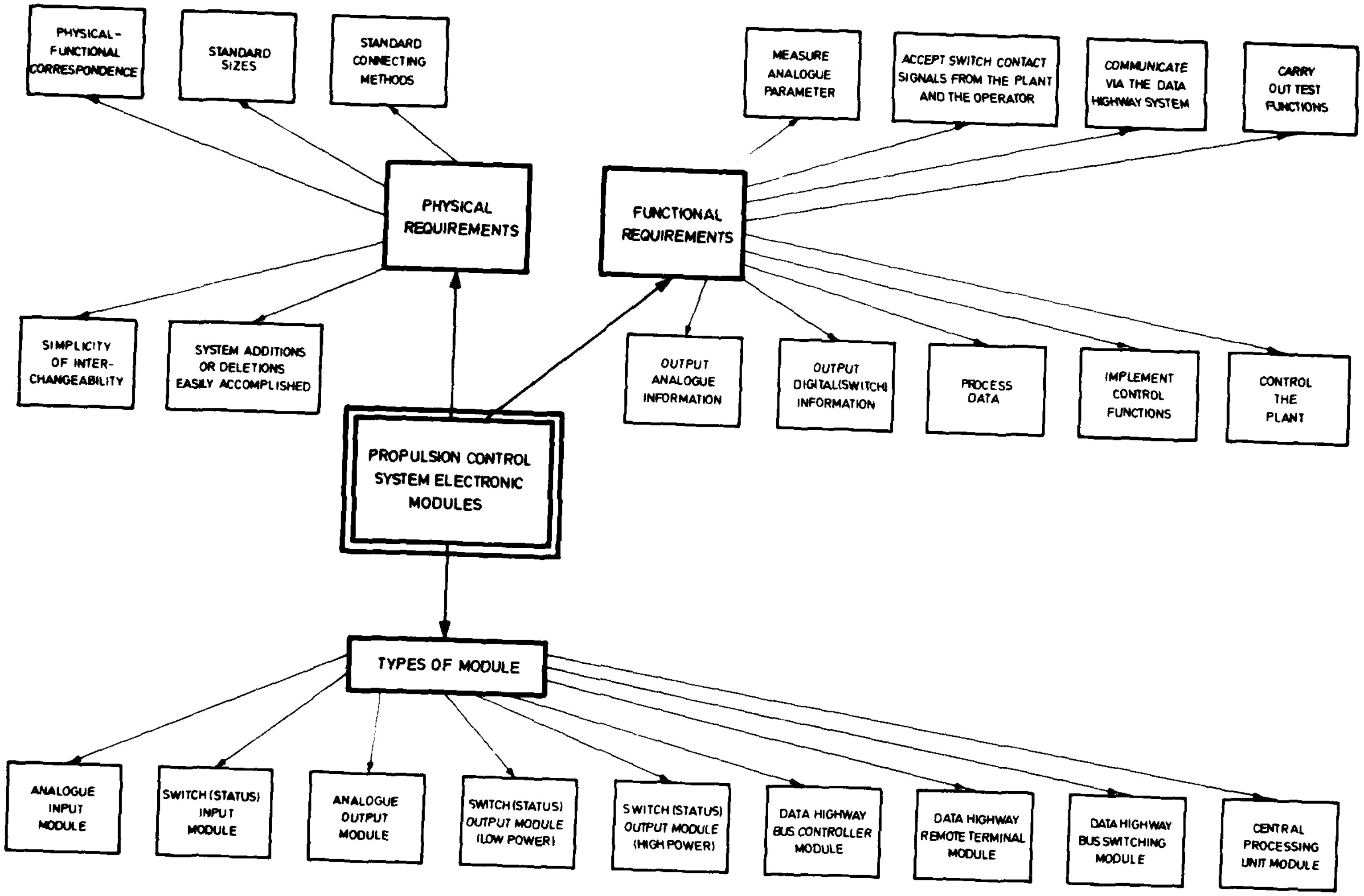
(3) "A Study of Standardisation Methods for Digital Guidance and Control Systems", AGARD Advisory Report No. 90, May 1977.

(4) J.D. McGonagle, "Structured Software Study", U.S.A.F. Avionics Library Wright Patterson A.F.B., Project No. 6090 October 1974.

(5) J.E. Cooling, A.R. Cuff, "Digital Data System - Data error rate performance on a Type 42 Destroyer" Marconi Internal Report ST/77/8134.

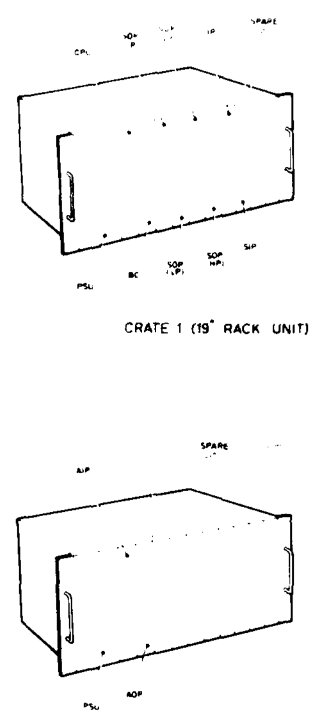


Propulsion control system equipment-one shaft set (COGAG fit) Fig. 1

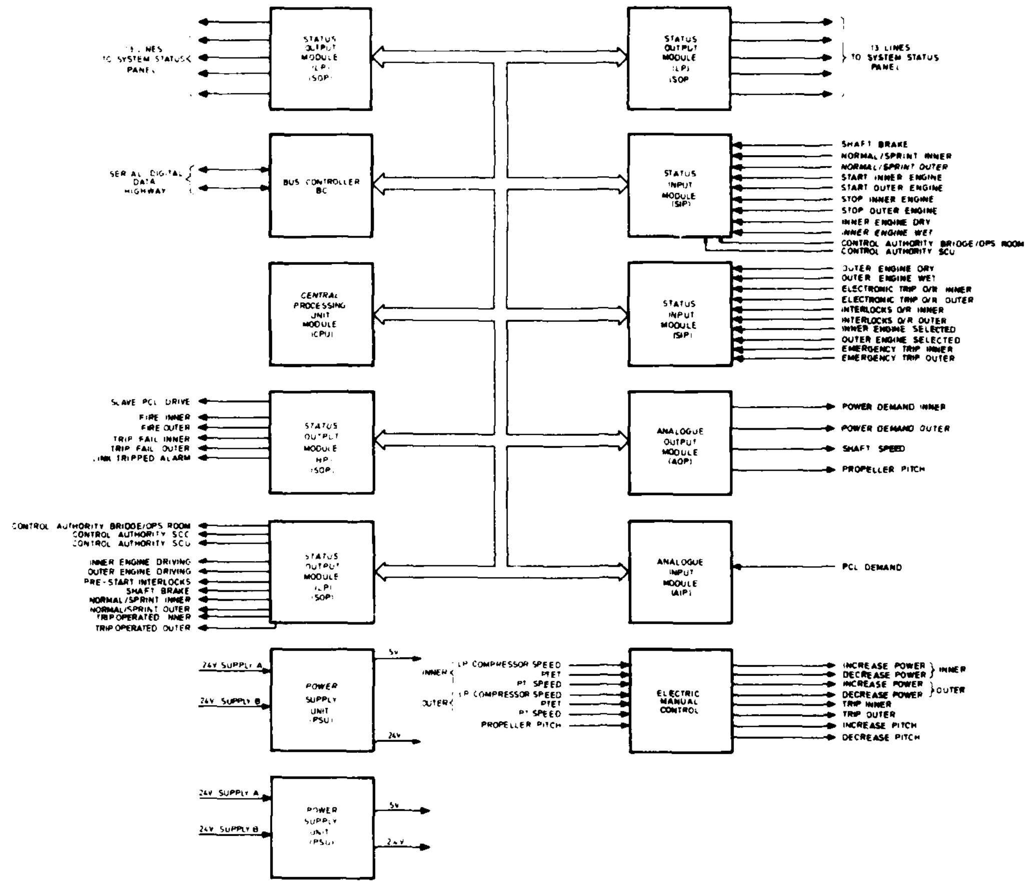


Modular structure of the control electronics

Fig. 2



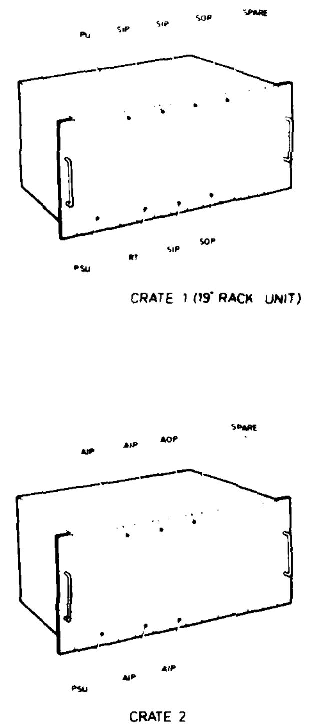
3(a) Physical packaging



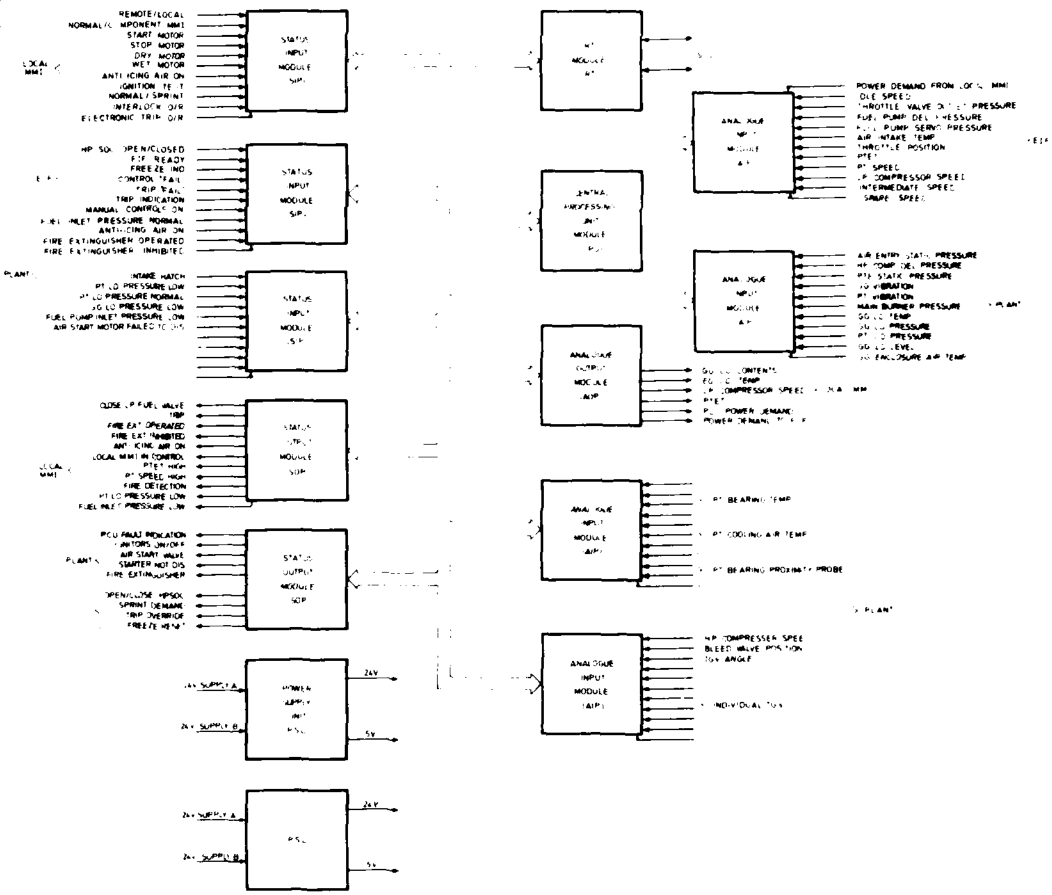
3(b) Functional diagram

SCC console - one shaft set (control electronics)

Fig. 3



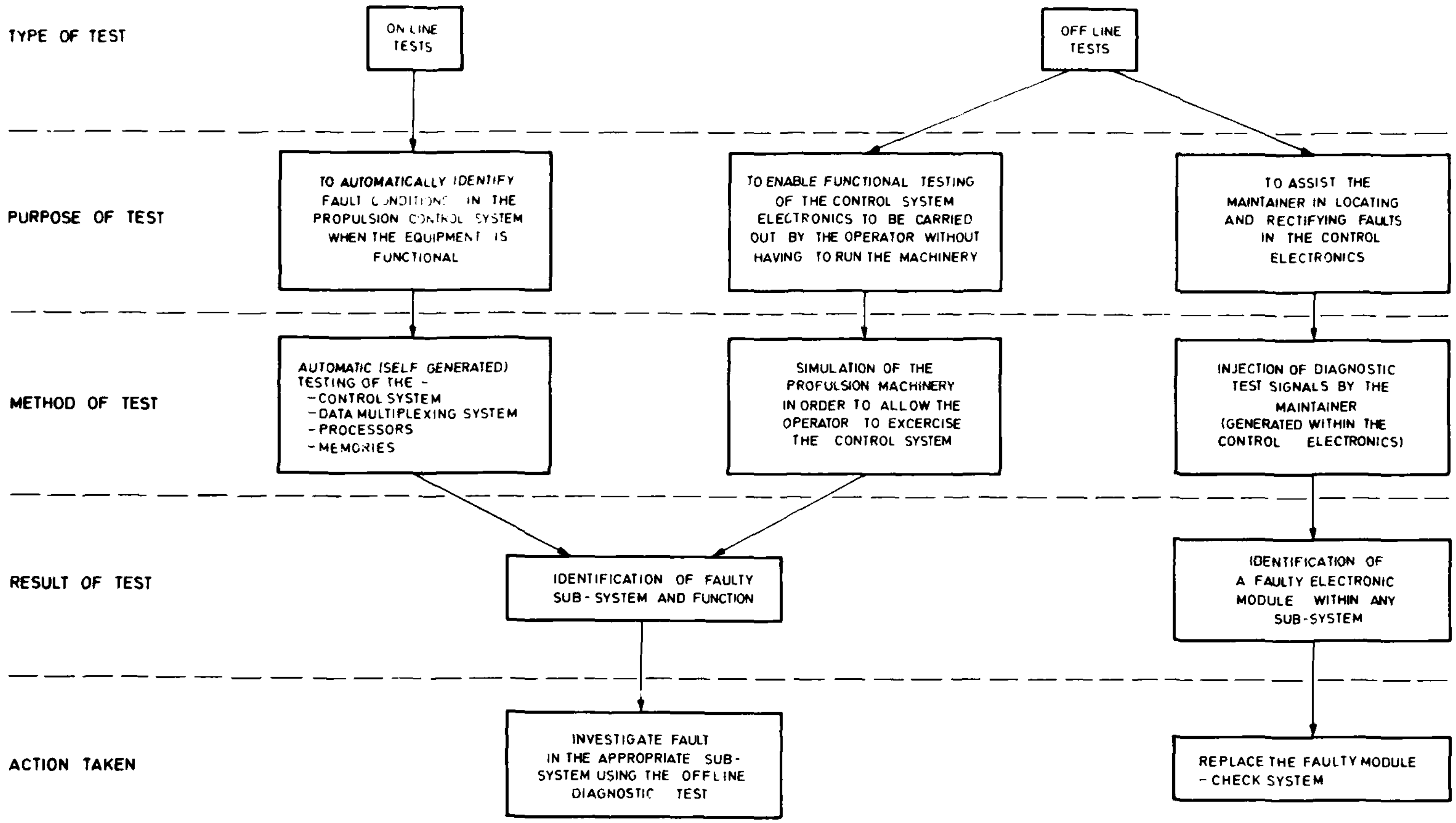
4(a) Physical packaging



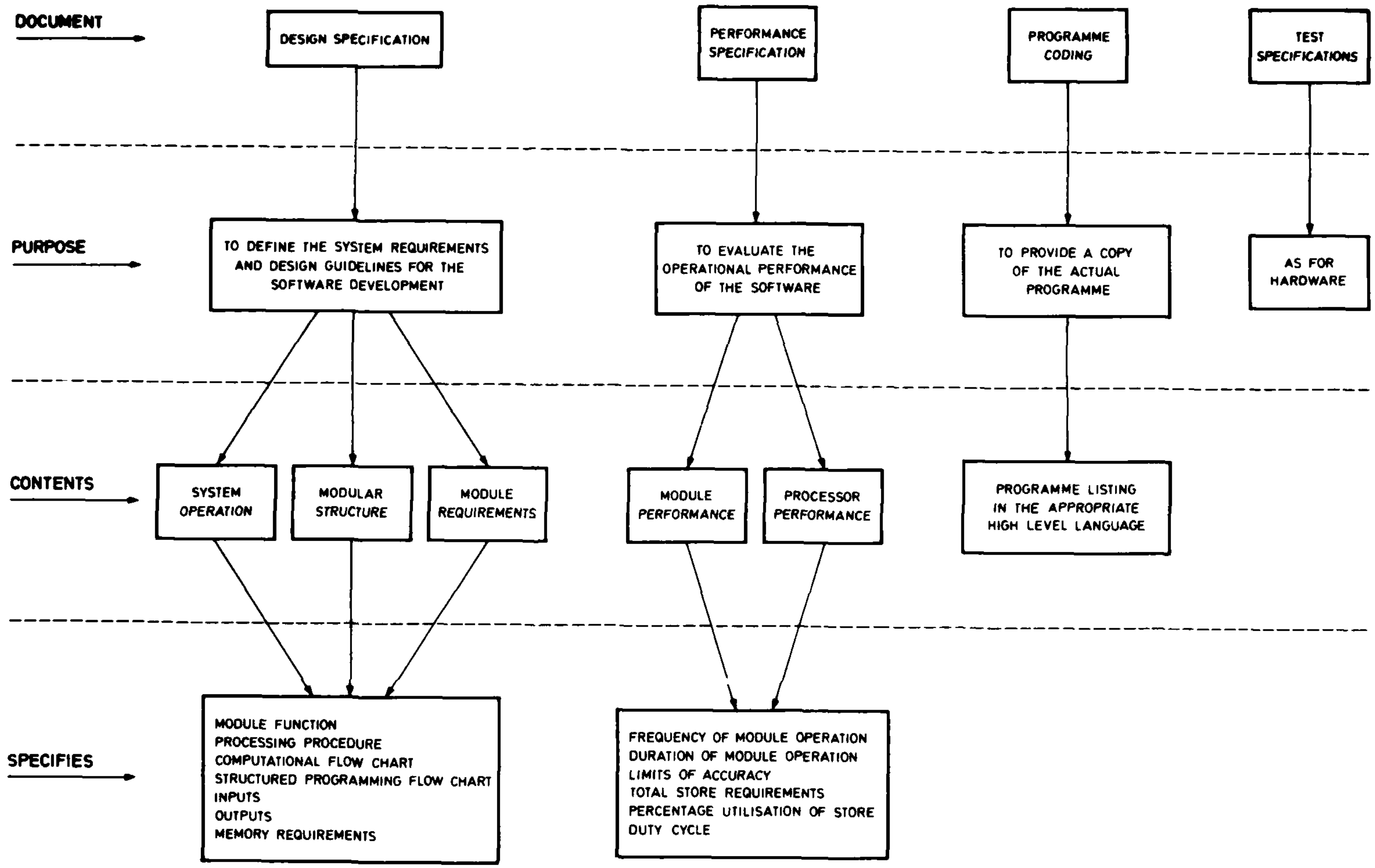
4(b) Functional diagram

Typical gas turbine control system configuration

Fig. 4



Built in test facilities Fig. 5



Software documentation Fig. 6

LIST OF SYMPOSIUM AUTHORS, SESSION CHAIRMEN,
AND GUEST SPEAKERS

	Volume	Session	Page
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Simanowith, R. C. David W. Taylor Naval Ship R&D Center	5	R	2-1
Smalley, J. P. E. EASAMS, Ltd (UK)	4	O1	1-1
Smith, W. E. David W. Taylor Naval Ship R&D Center	6	P	2-1
Spencer, J. B. Chairman, Session K2 Ministry of Defence (UK)	1	A	2-1
Stankey, R. Chairman, Session E1 Naval Ship Engineering Center			
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Thomas, J. R. E. Ferranti (UK)	2	E1	2-1
Thompson, R. V. Univ of Newcastle Upon Tyne (UK)	5	Q2	2-1
Tiano, A. Laboratorie per l'Automazione Navale (Italy)	4	P	4-1
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