AN EVALUATION OF PROPULSORS FOR SEVERAL NAVY SHIPS

by

MARK A. HUGEL
B. S. Systems Eng., United States Naval Academy
(1977)

SUBMITTED TO THE DEPARTMENT OF
OCEAN ENGINEERING
IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREES OF
MASTER OF SCIENCE IN NAVAL ARCHITECTURE AND MARINE ENGINEERING
and
MASTER OF SCIENCE IN MECHANICAL ENGINEERING
at the
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
June, 1992

Signature of Author ______________________
Department of Ocean Engineering
May,1992

Certified by ______________________
A. Douglas Carmichael
Thesis Supervisor

Certified by ______________________
David G. Wilson
Thesis Reader

Accepted by ______________________
A. Douglas Carmichael
Department Graduate Committee
Department of Ocean Engineering

AN EVALUATION OF PROPULSORS
FOR SEVERAL NAVY SHIPS

by
MARK A. HUGEL

Submitted to the Department of Ocean Engineering
on May 8, 1992 in partial fulfillment of the
requirements for the Degrees of Master of Science in
Naval Architecture and Marine Engineering and
Master of Science in Mechanical Engineering

ABSTRACT

A project was undertaken to develop a relatively simple computer program which models the performance, weight, volume and cost of various combinations of propulsion plant components for three different naval ship types. Within that computer program, the types of propulsors from which the user may select include fixed pitch propellers, controllable reversible pitch propellers, contrarotating propellers, propeller/pre-swirl vane combinations, and waterjets. The propeller choices include both ducted and non-ducted configurations. To model these propulsors in a computer program, routines were developed to select the correct propulsor geometry to transmit developed horsepower to the water, and to predict the off-design performance, weight and (if applicable) volume of the propulsors chosen.

Propeller geometry design and off-design performance for the propeller variants were characterized using the Propeller Lifting Line computer program developed at MIT. Waterjet performance was predicted using information obtained for *KaMeWa* waterjets. Correlations describing optimum propeller geometry versus thrust coefficient, propulsor performance versus ship speed, propulsor weights and volumes were developed for the different ship types. These correlations are invoked within the propulsor modelling routines in the program, thereby allowing the propulsors to be matched with various engine and transmission combinations. The computer program logic is outlined which is used to match the size and performance of the chosen propulsion components with a hull sized to envelope the propulsion plant and a fixed payload. Details are included to describe the workings of the propulsor model included in the program, and specific differences between the destroyer and amphibious ship propulsor models are discussed. Results of the propulsor routines used in the program are graphed for these two ships allowing a comparison of propulsor types for various ship displacements.

Thesis Supervisor: Dr. A. Douglas Carmichael
Title: Professor of Power Engineering

Acknowledgments

The author would like to thank several people who provided assistance during the course of this project.

Dr. A. Douglas Carmichael conceived the project and awoke many nights with inspiring ideas to guide this effort. His insight proved invaluable and his patience was immeasurable.

Dr. Justin E. Kerwin provided access to the computer modelling tools and assisted greatly in ensuring that realistic propeller design results were obtained. He also patiently answered many questions during the past several months. He and Dr. Ching - Yeh Hsin were gracious enough to provide access to the supercomputer propeller design account, only to have the author crash the system during its use.

Finally, a special thanks to Luana, Joshua and Chelsea, who helped to provide a good balance between being a student, husband and father. Their love and support were ever present.

Table of Contents

List of Figures

Chapter One

Introduction

The design of a naval warship involves a complex and iterative cycle of decisions and tradeoffs. In order to begin the process, choices of the desired payload, size, maneuvering characteristics and eventual cost are a few of many that must be made to assure that the design team is apprised of the objectives, requirements, philosophy and constraints of the design effort. Another important decision which must be made early in formulating the foundation of the design is the selection of technologies which are to be included during the design process.(1)

Many propulsion technologies have been, and are being, employed on naval warships, and many more have been proposed. Selection of propulsion technologies must be made early in the design process, as changing technologies later in the process would have too large an impact on the design to be feasible. A method of modelling the available technologies would facilitate comparative assessments and would promote the chance of choosing the best propulsion plant for a new design correctly. This paper describes a portion of a larger project whose goal is to provide a computer model of propulsion plant technologies to aid the process of selecting competing technologies during the conceptual stages of the design of several naval ships.

Background

In some areas of ship design (notably portions of the combat system suite) it is desirable to loosely define desired technologies in the very early stages of the design since the state-of-the-art for many combat systems components can dramatically change during the several years from design conception to physical construction. For other areas of ship design (such as the hull form and propulsion plant) technology choices must be made early in the process, and little or no flexibility exists in changing these choices at any time later in the design, because of the impact that these systems and their components have on the entire design. With so much dependent on making the "best" selection of technologies for incorporation into these high impact systems at the very beginning of a several year design and construction effort, a means to select the "best" technologies based in quantitative analysis rather than subjective selection would improve the likelihood of making the correct choices.

In today's political and economic environment, the emphasis on what is important in naval ship design has shifted within the past year from obtaining maximum performance at high cost to obtaining satisfactory performance to meet the mission demands at the lowest cost possible. An example of this emphasis shift can be seen in the recent decision to scrap the DDG-51 Flight III design (maximum performance at high cost) in favor of DDG-51 Flight IIA (performance to fulfill the mission at the lowest cost feasible). This shift in emphasis shows how difficult selecting the "best" technologies can be, since "best" can mean many different things. It does not mean however, that statistically based assessments of potential technologies should be scrapped; rather this points to a need for models which predict the performance of comparable technologies in an unbiased manner. The results predicted by these models for comparable technologies can then be graded using whichever criteria is important (either technically or politically) to determine the "best" choice.

One area that lends itself to this type of technology modelling is the selection of propulsion plant components. Size, weight, performance and cost of existing naval ship propulsion plants is well documented and comparable information for several newer technologies can be obtained or predicted. By using these data to develop correlations for the various technologies, it is possible to build computer models which allow for choosing different combinations of engines, transmissions and propulsors for different ship designs which produce predictions of performance and cost of each combination. These predictions can then be compared using criteria established by the assessor to decide the best combination of components for the design at hand.

Project Overview

This paper describes a portion of a project undertaken to develop personal computer based models for propulsion component evaluation for three Navy ship types. Since each of these ship models allows for combining various engines, transmissions and propulsors, a three by three matrix representation of the scope of this project was devised and is provided in Figure 1.

For each ship type, important characteristics such as size, displacement, payload to be carried and desired performance (speed and endurance) were chosen to define a baseline configuration. For the surface ships, a typical gas turbine/mechanical transmission/controllable reversible pitch (CRP) propeller combination serves as the baseline propulsion plant since performance for this combination is widely understood. For the submarine, the emphasis of this project is to evaluate air independent power sources against a baseline nuclear power plant and, as a result, the propulsor choice is limited to contrarotating propellers, and transmission choices are also limited.

Matrix of Ship Types and Propulsion System Components

	Destroyer	LX Amphibious Ship	Submarine
Power Source	- LM-2500 gas turbines - I/CR gas turbines - Diesels	- LM-2500 gas turbines - Diesels	- Fuel cells - Closed Brayton cycle - Stirling cycle - Semi-closed cycle diesel - Diesel/electric - Aluminum /Oxygen cell
Transmission	- Geared mechanical - Mechanical with TOSI coupling - Epicyclic gear - AC electric (with and without epicyclic gears) - DC electric	- Geared mechanical - AC electric (with and without epicyclic gears) - DC electric	- Geared mechanical
Propulsor	<u>Propellers</u> - Fixed pitch - Controllable reversible pitch - Contrarotating - Fixed pitch with preswirl stator - Ducted versions of the above <u>Waterjets</u>	<u>Propellers</u> - Fixed pitch - Controllable reversible pitch <u>Waterjets</u>	- Contrarotating

Figure 1

Several methods can be employed to assess the impact of propulsor component variations on a ship design. These include payload fixed or payload limited and propulsion plant fixed or propulsion plant limited.[2] The method employed in this study requires the payload to be fixed, the propulsion system component types and numbers to be fixed, and then a geometrically similar (*geosim*) ship is sized to be as small as possible to contain the payload and power plant. The ship endurance is held constant for each propulsion system variation; this serves as a constant to establish the impact of propulsion efficiency.

In order to predict operating and life cycle costs, assumptions have been made regarding the operating profiles of each ship type, other economic factors (cost estimating methods, discount rates, etc.) and projected number and lifetimes of ships to be built. These assumptions are to be applied consistently to each component variant taking into account the impact of each variant on volume, weight, fuel requirements and changes in crew manning.

Propulsor Evaluation

The characterization of the various propulsors listed in Figure 1 involved choosing a method to predict propulsor efficiency and cavitation performance for each of the three ship types over a range of speeds, displacements and number of propulsors in each design. The propeller performance model chosen was the

Propeller Lifting Line (PLL) computer program (developed by Professor J. E. Kerwin's propeller design group in the Department of Ocean Engineering, MIT). This modelling program was chosen because it has the capability to predict performance for all propeller types included in the project over the range of thrust and speeds required for each ship type. This program's vortex lattice method of predicting single propeller performance produces results which are consistent with performance predictions for single propellers when applying Lerb's theory (which produced the most accurate performance predictions of the lifting line methods).[3]

It was proposed to determine actual rather than ideal performance so that the predictions of the computer program being developed for this project are realistic, and PLL includes features to satisfy this goal. Since PLL has not been used for this type of study in the past, it became necessary to correlate PLL propeller designs with some realistic measure of cavitation performance (since ideally PLL designs cavitation-free propellers). Off-design performance data for PLL designed propellers was also needed in order to evaluate annual fuel costs for the operating profiles studied.

Although waterjets have not been used in large naval surface ship applications to this point, there have been proposals that waterjets could be used for this purpose, particularly in combination with other propulsors. It has been shown in some cases, that the lack of appendage drag as a result of using waterjets more than compensates for higher inefficiencies of waterjets when compared to propellers, and a higher propulsive coefficient is attainable.[4] Since no computer model was available to predict waterjet performance, information was obtained from the Swedish waterjet manufacturer *KaMeWa*, which is considered to be a world wide leader in waterjet technology. The waterjet performance information was correlated in a fashion similar to propeller performance data in order to allow for a fair comparison of results.

Weight, volume and cost correlations for propellers and waterjets were included in the propulsor modelling program so that the impact of differences in these areas could be included within the *geosim* ship concept described earlier.

To provide two examples of how the data collected for the various propulsors is used, the development of the propulsor modules used in the destroyer and amphibious ship power plant models are discussed in this paper. The propulsor modules include code for selecting a propeller geometry which is the most efficient for the required thrust and satisfies cavitation criteria established prior to data collection. Once the geometry is fixed, off-design data correlations are used to establish propulsive coefficient and propeller rotational speed (revolutions per minute) at maximum speed and cruise speed. Volume, weight and cost correlations are then used to establish the propulsors' contribution to the *geosim* ship's size and acquisition cost. Finally, off-design data correlations provide predictions of propulsive coefficient and propeller revolutions per minute (rpm) over the operating profile, which are used to determine annual fuel costs for the combination of propulsion components being assessed.

Chapter Two

Using PLL to Predict Propeller Performance

A Description of PLL

The use of lifting line theory to model propeller performance has been developed within the past seventy years, beginning with Prandtl, Betz and Goldstein. Although the early efforts in this area were aimed at modelling high aspect ratio aircraft propellers, the high aspect ratio assumption had no bearing on the ability of this method to predict forces on the propeller, which is an important part of preliminary marine propeller design. One drawback in applying lifting line techniques to propeller design was the large number of tedious calculations necessary to obtain results. In 1952, Lerbs published the most advanced and accurate of these methods, but without today's computing power available, Lerb's theory was not widely applied.[5]

More recently, preliminary propeller design using lifting line theory has been made feasible by programming the tedious calculations to be performed by computers. As the computing capabilities have grown, so have the ambitions of the programmers, resulting in the logical extension of these numerical methods to multiple component propulsors. While the Lerb's method worked quite well for single propellers, the additional desire to model multi-stage and ducted propellers with accuracy comparable to Lerb's theory required developing a computer program which optimizes blade loading using a lattice of discretized constant vortex segments. This program, known as the MIT Propeller Lifting Line program (PLL), has been developed and refined at MIT over the past six years by Kerwin, Coney and Hsin.[6,7,8,9]

PLL serves as a tool for the preliminary design of propellers. It includes the capability to model numerous propeller types including

- variable pitch,
- contrarotating,
- propeller and pre- or post- swirl stator combinations,
- ducted versions of the above, and
- ringed propellers.

PLL allows the user to vary inputs such as ship speed, propulsor diameter, number of blades, hub centerline depth, desired thrust (or thrust coefficient) and propeller rotational speed (or advance coefficient) and then parametrically study the effects on efficiency, cavitation, strength and cost of the PLL designed propulsor.[10] A detailed description of the lifting line theory and vortex lattice methods employed by PLL as well as complete details regarding the use of PLL are provided in reference 10, the PLL User's Manual.

Generating Wake Velocity Files for Use by PLL

In order for PLL to calculate forces induced throughout the vortex lattice representation of the propeller blades, the user is required to provide PLL with information describing the propeller inflow velocities. This information is provided in the form of wake files, which are formatted to be read by PLL during a PLL design session. Since the wake velocity profiles of the three ships studied during this project were different, separate wake files were generated for each ship type. These files contain axial, radial and tangential components of the wake field which are defined in terms of harmonic coefficients of the circumferentially varying inflow at specified radii.[11] The harmonic coefficients are determined by fitting Fourier cosine and/or sine series curves to the inflow velocities at each radius.

To produce the destroyer wake file, a wake velocity file for DDG-51 was obtained from David Taylor Model Basin. This file contained axial, radial and tangential inflow velocities at six different radii gathered during model testing of the DDG-51. This data was plotted, and curve fitting was done using the

"EasyPlot" plotting computer program to obtain the harmonic coefficients needed by PLL. The PLL wake file for the destroyer is included in Appendix 1.

To produce the amphibious ship wake file, a wake velocity file for the LSD-49 amphibious transport ship was obtained from David Taylor Model Basin. Like the destroyer wake field file, this file contained axial, radial and tangential inflow velocities at six different radii gathered during model testing. These data were plotted, and the harmonic coefficients obtained by curve fitting these data are included in the PLL wake file for the amphibious ship, which can be found in Appendix 1.

The PLL wake file for the submarine was constructed using a wake contour diagram for a submarine, which was extracted from the course notes for the MIT Professional Summer Submarine Design Course taught by Captain Harry Jackson, USN (Ret.). The wake contour diagram was marked at each tenth of a radius from the hub to the tips, and each radius was subdivided into 45 degree increments. The velocity at each radius was then averaged using the velocity at each 45 degree increment, and these mean velocities were formatted into the PLL submarine wake file found in Appendix 1. To verify the accuracy of this method, the Submarine Design Course notes include methods for calculating the wake fraction of a submarine using correlations based on the hull design. Employing those methods to a typical, modern nuclear-powered submarine hull resulted in a wake fraction prediction of 0.637. PLL computes a wake fraction based on the wake file it is provided, and the submarine wake file which was generated as described earlier resulted in a PLL predicted wake fraction of 0.635.

Generating PLL Input Files for the Different Ship Types

In addition to information describing the ship's wake velocity field, other information pertaining to the ship design which affects propeller performance must be provided to PLL. This information includes hub centerline depth, propeller diameter and (if used) duct dimensions. Therefore, prior to beginning the propeller design process, predictions of these parameters needed to be made.

For the twin screw destroyer, the DDG-51 propeller diameter of 17 feet was chosen for PLL runs, although data related to propeller diameter was collected in non-dimensional form using the propeller advance coefficient J defined by

$J = V_a / (n^*D_{prop})$ where V_a = speed of advance, ft/sec
n = shaft rotational speed, revs/sec
D_{prop} = propeller diameter, ft .

Hub centerline depths were varied over a range of 15.2 to 17.95 feet, depending on the displacement of the ship (four displacements ranging from 8300 to 9500 LT were used). These centerline depths were obtained by running the Advanced Ship

Synthesis Evaluation Tool (ASSET) with a DDG-51 input file obtained from NAVSEA.

The propeller diameter used for amphibious ship propeller design was 16 feet, which matches the diameter of a version of the proposed LX design. Hub centerline depth of the LX was known for a 22,700 LT displacement. Tons per inch immersion (TPI) was calculated using typical amphibious ship hull design parameters, and this was used to adjust hub centerline depths over the range of displacements.

The diameter selected for the submarine propeller was 18 feet based on information gathered from the propeller design portion of course notes from the MIT Professional Summer Submarine Design Course. The hub centerline depth for the submarine propeller was set at 200 feet in order to evaluate propeller designs against the cavitation criterion described later.

The dimensions of the ducts (for those propeller designs incorporating ducts) were arrived at based on typical duct dimensions described by Coney.[12] Copies of the PLL input files which contain all the parameters discussed above are included in Appendix 2.

Correlating PLL Designed Propellers to Realistic Cavitation Performance

A goal in using PLL for this project was to attempt to predict propulsor performance as realistically as possible. With this goal in mind, a limitation in using PLL is that PLL calculates propeller optimum blade thickness and camber to produce a propeller which is cavitation-free presuming steady circumferential inflow at each radius. (As discussed earlier, the wake velocity profile provided to PLL by the user contains velocities which represent the circumferentially averaged velocities at each control radius.) Blade thickness and camber are optimized by adjusting them to enable each propeller design to operate at the optimum point on the associated minimum pressure coefficient versus variation in angle of attack plot (known as a cavitation "bucket" diagram). Figure 2.1 was excerpted from the PLL User's Manual to graphically display this idea.

Unfortunately, propellers are normally placed near the stern of ships where the wake produced by the ship's hull affects the inflow velocity field of the propeller(s). The shafting support struts are also located directly forward of the propeller(s), which further disrupts the inflow. The result is a propeller inflow velocity field which is anything but circumferentially steady, as must be assumed when using the vortex lattice lifting line method in PLL. So, while PLL optimizes blade thickness and camber to assure that the output propeller operates at the point

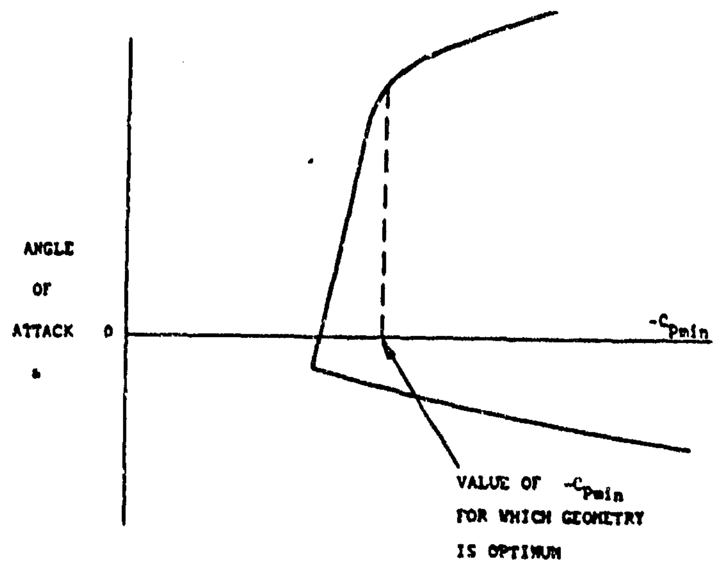


Figure 2.1: Illustration of cavitation "bucket" with optimum operating point indicated

(excerpted from *MIT-PLL User's Manual*).

shown on Figure 2.1 in circumferentially steady flow, actual propeller cavitation performance in unsteady inflow would fall within a region of the "bucket" diagram as depicted in Figure 2.2. Whether or not the region of actual propeller performance would remain within the non-cavitating portion of the bucket diagram depends on the amplitude of circumferential variance of the velocities from the mean at each radius. Within the numerical methods of PLL, no method exists to analyze the effects of unsteady inflow (and therefore more accurately predict actual cavitation performance), so a different method to evaluate the cavitation performance of PLL designed propellers was deemed necessary for this project.

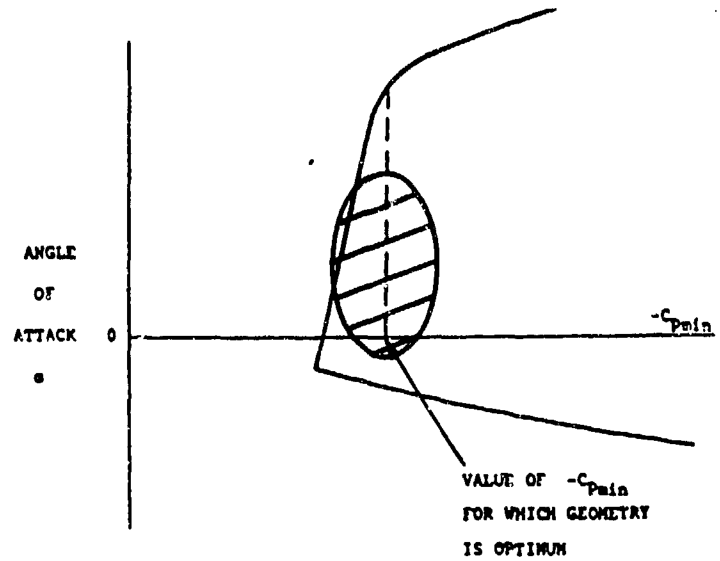


Figure 2.2: Illustration of cavitation "bucket" diagram with a typical operating regime in unsteady circumferential flow indicated.

One criterion historically used by propeller designers to choose sufficient blade area to avoid excessive cavitation was developed by Burrill in 1943.[13] A particular propeller's cavitation performance can be compared to other propellers by plotting the propeller's blade thrust loading coefficient versus local cavitation number on a "Burrill chart", which has regions defining percent back cavitation diagramed for various propellers. Burrill chose a non-dimensional coefficient, τ_c, as a way of characterizing the blade thrust loading which accounts for propeller geometry features including expanded area ratio and pitch-to-diameter ratio. This coefficient is defined by

$\tau_c = T / (A_p * q_r)$ where T = thrust, lbf
A_p = projected blade area, sq ft

$q_r = \frac{1}{2} * \rho_{sw} * V_r^2$
V_r = relative water velocity at 0.7 tip radius.

The local cavitation number used on a Burrill chart is calculated at 0.7 tip radius using the following equation

$\sigma_{0.7} = (p_s - p_v) / q_r$ where $p_s - p_v$ = pressure at hub centerline, psi
q_r same as defined above.

Since the Burrill criterion has been widely used in preliminary propeller design, and PLL includes all relevant information in its output to determine a PLL designed propeller's cavitation performance when evaluated using this criterion, it was chosen as the tool to be used in realistically evaluating potential cavitation performance. To verify that this tool would prove useful in comparing PLL propeller designs, numerous PLL runs were made using speed-power information for a DDG-51 while varying ship speed and advance coefficient and then plotting the resulting propeller cavitation performance on a Burrill chart. Figure 2.3 shows that the PLL designs could be easily evaluated using the Burrill criterion, as the designs were well separated from each other when plotted on a Burrill chart in this method.

Once it was determined that this technique would be useful in comparing cavitation performance of various PLL designs, cavitation performance standards needed to be established for each of the ship types. For the destroyer and

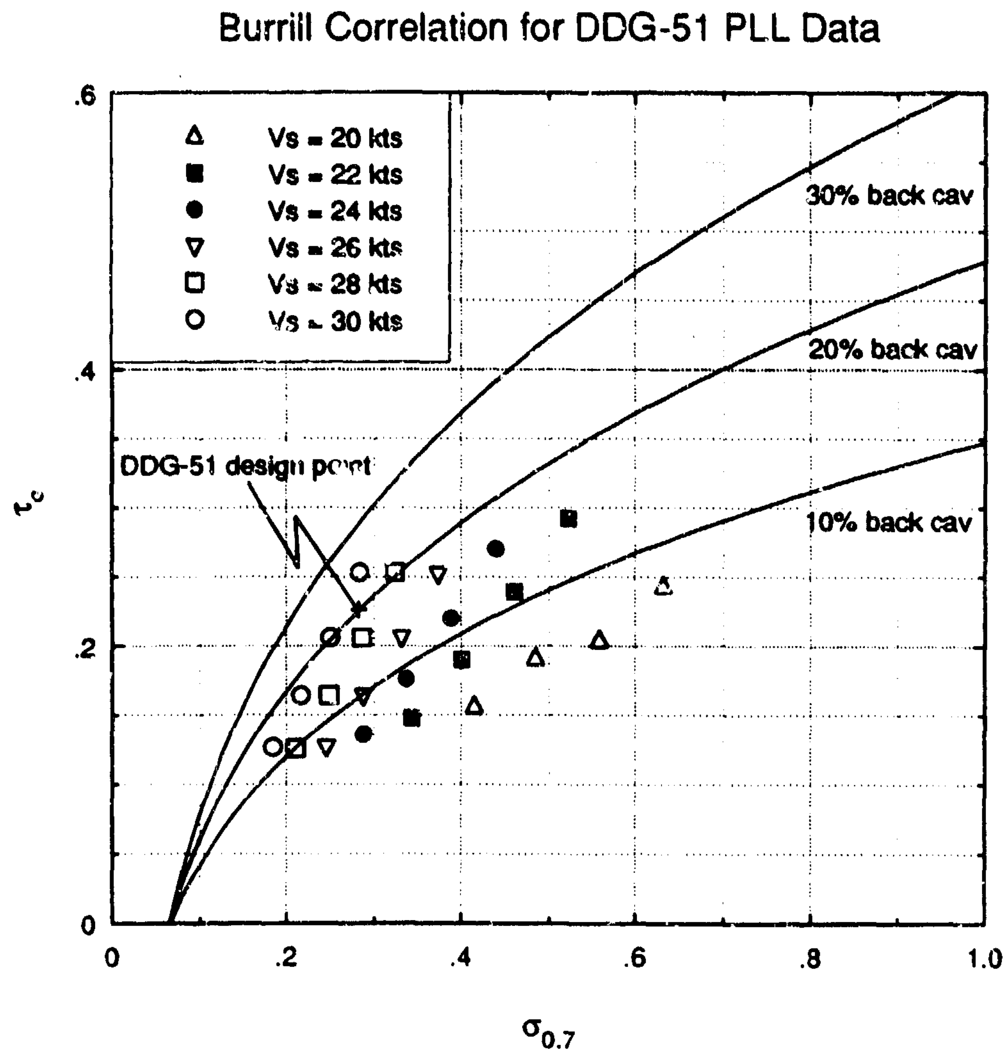


Figure 2.3: PLL-designed propeller performance when evaluated using Burrill cavitation criterion. Data points were taken at varying advance coefficients (J) at the speeds indicated. The DDG-51 design point marks the cavitation performance of the PLL-designed propeller which was the most geometrically similar to the actual DDG-51 propeller and matched the speed vs rpm relationship of the DDG-51 propeller at the speed indicated.

amphibious ship, the geometry for the propellers chosen for the respective ship types was known. It was noted from the PLL output, for example, that the propeller geometries of the propellers which PLL optimized to operate at 28 knots and 30 knots bounded the geometry of the propeller chosen for use on DDG-51. By making several more PLL runs using DDG-51 speed-power information in the 28 to 30 knot regime, the DDG-51 propeller geometry was matched by PLL at 29 knots ship's speed. This propeller's cavitation performance was plotted on a Burrill chart (see Figure 2.3) which resulted in 20.7 percent back cavitation. Since the propeller geometry, rotational speed and thrust produced match the DDG-51 design closely, it was felt that this propeller's cavitation performance must closely resemble the cavitation performance of DDG-51's propellers, which the Navy considers satisfactory. Thus, the cavitation standard to be used in evaluating all other PLL-designed destroyer propellers was established at 20.7 percent back cavitation while operating at 29 knots ship speed and the corresponding thrust.

In a similar manner the amphibious ship propeller geometry was matched using PLL. The Burrill cavitation performance standard for this ship type was established at 14.5 percent back cavitation at 23.25 knots ship speed and the corresponding thrust.

The cavitation standard for the submarine propeller was not carried out using the same method as for the surface ships since actual submarine propeller geometry information was not available. Instead, it was decided that since the submarine design was to have a maximum speed of 27 knots, it would be desirable that the propeller did not cavitate (that is, zero percent back cavitation) up to the maximum speed when the submarine was submerged with the hub centerline at or below 200 feet. PLL runs were then made to assure that this cavitation standard could be met by contrarotating propellers over the expected range of thrusts. This standard proved to be feasible, and was therefore adopted.

As stated earlier, realistic cavitation performance predictions were a goal of the propulsor design. To this end, PLL allows for unloading the propeller hub and blade tips while optimizing blade loading, which is desirable to minimize sources of cavitation. This feature was employed to ensure that the propellers designed for this project using PLL exhibit the best possible cavitation performance, given that the tool being used is intended for preliminary propeller design. The effect of hub and tip unloading resulted in open water efficiency predictions for the various propeller designs being several percent less than efficiencies of the same propellers with no effort to unload the hub and tips; however, this tradeoff was felt to be in keeping with the intent of producing realistic performance results.

Propeller Design Performance

Once the cavitation performance standard for each ship type was defined, determination of satisfactory propeller designs was begun. Since each propulsor type would be combined with various types and numbers of transmissions and engines, the resulting geosim ships could be expected to vary somewhat in size and displacement from the baseline ship of each type. The variance in displacements would result in different speed-power curves for each *geosim* ship, and therefore it became necessary to exercise PLL not only to find propeller designs which satisfied the cavitation criteria, but also which produced a range of thrusts at the design conditions (the design conditions being 29 knots at the corresponding thrust for the DDG, 23.25 knots at the corresponding thrust for the amphibious ship, and 27 knots at the corresponding thrust for the submarine).

Once satisfactory propeller designs were generated using PLL, a method which could be simply programmed to choose the most efficient propeller geometry which produced sufficient thrust was needed. One method offered by Manen (1966) to compare optimum propulsor efficiencies for various types of propulsors involved comparing open water efficiency versus a non-dimensional torque coefficient b_q where

$$b_q = K_Q / J^5 \quad \text{and} \quad K_Q = \text{propeller torque coefficient}$$
$$J = \text{propeller advance coefficient}$$ [14]

For this project, since thrust, rather than torque, was the variable of interest, a similar approach to Manen's, comparing open water propeller efficiency versus a non-dimensional thrust coefficient, was seen as the method to choose the optimum propeller geometry. The thrust coefficient chosen was C_T, where

$$C_T = T / (\tfrac{1}{2}\rho_{sw} V_s^2 A_p) \quad \text{and} \quad T = \text{thrust, lbf}$$
$$V_s = \text{ship speed, ft/sec}$$
$$A_p = \text{propeller disc area, } \pi D_{prop}^2 / 4 .$$

Once this method was settled upon, PLL was repeatedly run for the various propeller types of interest. The required thrust was varied and the propeller designs which 1) satisfied the cavitation performance standard for the ship type, and 2) showed the optimum open water efficiency, were identified. Propeller designs which had higher efficiencies but did not satisfy the Burrill cavitation standards for the respective ship type discussed earlier were eliminated from consideration at this point, so that all possible propeller designs selected from the remainder were known to meet the cavitation standard developed during this project. Graphs of the results are presented in Appendix 3 for the DDG propellers, Appendix 4 for the amphibious ship propellers and Appendix 5 for the submarine propellers. Comparisons of the design performance of the various propeller types being studied for each ship are provided in Figures 2.4, 2.5 and 2.6, which depict open water efficiencies for the various propeller options for the destroyer, amphibious ship and submarine, respectively. These comparisons show that the results of the PLL runs at design conditions are consistent with anticipated propeller performance; that is, the contrarotating propellers performed at about seven percent higher efficiency than fixed pitch propellers, propeller-preswirl stator combinations performed 3-4 percent better, and ducted propellers generally performed better than non-ducted versions of the same type.

Included on the graphs in Appendices 3, 4 and 5 are plots of the propeller geometry characteristics which also vary with changing thrust coefficient. Curves were fit to the data in these graphs, so that these curve fitting equations provide a correlation between required thrust and optimum propeller geometry. This provides the means to select the optimum propeller geometry of a particular propeller type (which exhibits satisfactory cavitation performance) within a relatively simple computer program simply by

- defining the resistance of the geosim ship at the cavitation design speed,
- calculating the thrust coefficient based on ship resistance and number of propulsors available to generate the required thrust, and
- predicting optimum propeller geometry using the thrust coefficient and the relevant correlation equation.

Development of the computer program will be discussed later.

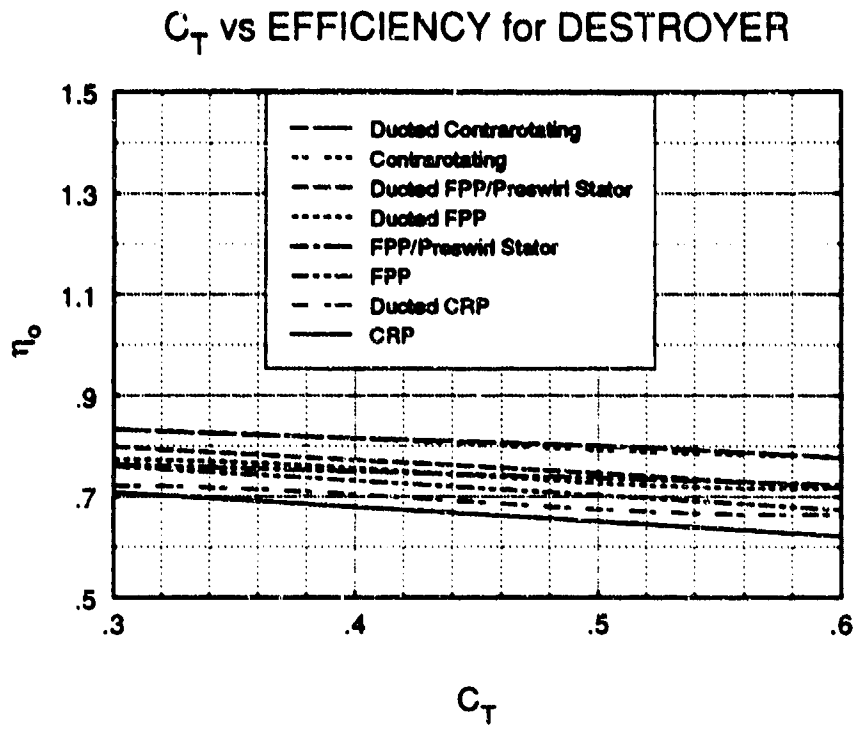


Figure 2.4: Destroyer propeller open water efficiency vs thrust coefficient, C_T.

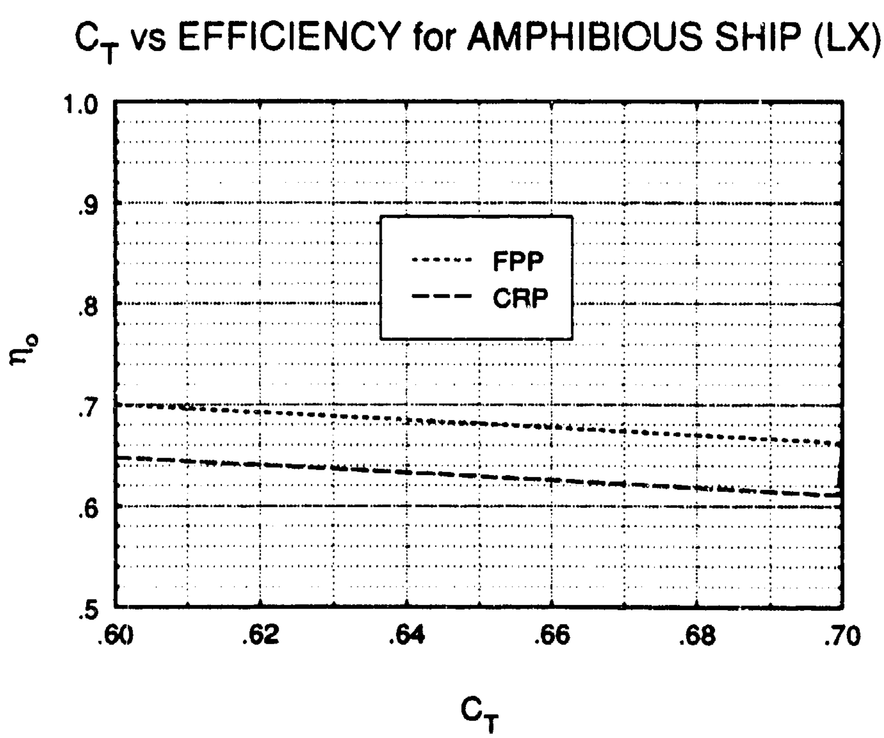


Figure 2.5: Amphibious ship propeller open water efficiency vs thrust coefficient, C_T.

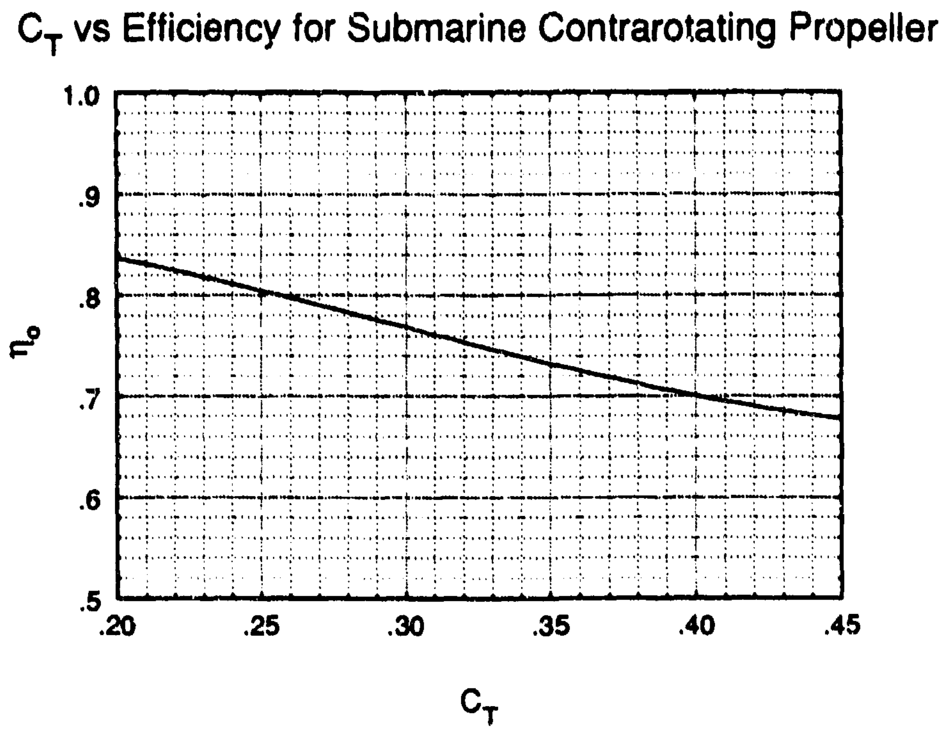


Figure 2.6: Submarine propeller open water efficiency vs thrust coefficient, C_T.

Chapter Three

Impacts of Propulsor Off-design Performance

Impact of Propulsor Off-design Performance on Sizing the Geosim Ship

Assessing the impact of a particular combination of propulsion components on a payload-fixed *geosim* ship design requires that the weight and volume of the propulsion plant components, propulsion auxiliaries and propulsion-associated tankage (hereafter collectively referred to as the propulsion group) be determined. Two performance attributes have the most affect on the weight and volume of the propulsion group:

- attainment of maximum speed as specified in the design objectives, and
- attainment of endurance range at cruise speed as specified in the design objectives.

Designing to satisfy these two objectives results in the characterization of propulsion component size (based on power developed to achieve maximum speed) and auxiliary and tankage requirements (based on carrying a sufficient fuel supply to meet the specified endurance range while the engines power the ship at cruise speed and the electrical generators produce the power necessary to meet the 24 hour average electrical load).

Assessing a particular propulsor's impact on propulsion group weight and volume requires determining the propulsor's capability to take the power developed in the engines and subsequently delivered to the propulsor via the transmission and shafting (known as developed horsepower or DHP), and transmit that power into the water to overcome the resistance of the sea to the hull and its appendages (known as effective horsepower or EHP). This capability is known as the propulsive coefficient of a propulsor and is defined by

$$(Q)PC = EHP / DHP = \eta_o \, \eta_{hull} \, \eta_{RRE}$$

where η_o = open water efficiency

η_{hull} = hull efficiency = $(1-t) / (1-w)$

η_{RRE} = relative rotative efficiency

and t = thrust deduction factor

w = wake fraction.

Knowing the propulsive coefficient of a particular propulsor type at high speed allows predicting the maximum possible ship speed based upon engine power installed and EHP necessary to propel the ship at a particular speed. The rotational speed (typically in revolutions per minute - rpm) of the particular propulsor at maximum speed must also be found so that the transmission gear ratio necessary to match maximum engine rpm with propulsor rpm can be determined.

In this project, since the number of engines, transmissions and propulsors, and the size of the engines are fixed up front, the size and weight of the propulsion components depend on only the size and weight of the propulsors and transmissions. The size (and therefore the weights) of these components depends on the optimum propulsor geometry (defining the propulsor size/weight) and transmission gear ratio and capability to transmit maximum engine power to the propulsors (defining the transmission size/weight). It will be shown later that a logic path can be mapped to use propulsor PC and the associated rpm at a projected maximum speed to size the propulsion plant components, and then iteratively match propulsion plant weight, size and maximum speed capability to a *geosim* ship weight, size and maximum speed performance.

To further define the size and displacement of the *geosim* ship, fuel tankage requirements must be determined. Knowing propulsor PC and operating rpm at cruise conditions, and the *geosim* ship hull resistance at cruise speed, the engine fuel consumption rate at cruise conditions can be calculated. By knowing engine fuel consumption rate, fuel rate of the auxiliaries providing electrical power at the 24 hour average electrical load, and the time necessary to spend at cruise speed to achieve the specified endurance range, fuel tankage capacity can be predicted. This series of predictions and calculations can be integrated into the logic path described above to ultimately size the *geosim* ship so that it is tightly wrapped around the fixed payload and propulsion plant, yet meets all performance objectives.

From the discussion above, the propulsor characteristics which must be found to assist in sizing the *geosim* ship are propulsive coefficient and propulsor rpm at maximum and cruise speeds. Chapter two addressed using PLL to choose optimum propeller designs at the design condition, which was defined based upon the ship speed and thrust inputs to PLL to assure that the variety of propeller geometries produced by PLL, and available to be selected from, all satisfied the cavitation standard established for each ship type. Since it was not likely that the design condition speed would match the maximum speed, and even less likely that it would match both maximum and cruise speeds, the development of a method to obtain off-design performance predictions (at least at cruise and maximum speeds) for propellers whose geometry was fixed to meet cavitation criteria became necessary.

Impact of Propulsor Off-design Performance on Ship Annual Operating Costs

Assessing the impact that a particular combination of propulsion components has on ship annual operating costs can be broken down into assessments of the following costs which are strongly influenced by the type and number of propulsion plant components included in a ship design:

- annual fuel costs,
- annual maintenance costs, and
- costs associated with special manning requirements (numbers of people and/or types of operating or maintenance skills) established by chosen components.

Of the three, fuel costs are directly affected by the type of propulsors chosen, while maintenance and manning costs are only of consequence when the propulsors selected are controllable reversible pitch (CRP) (resulting in costs to maintain the pitch control system) or waterjets (resulting in costs to maintain the jet control system). By a wide margin, the propulsor selection's affect on annual fuel costs outweighs the other costs (even for the CRP and waterjet options), so that a small improvement in propulsive coefficient can dramatically reduce costs over a typical thirty year ship lifetime.

In order to evaluate annual fuel costs, assumptions must be made regarding how much time during an average year a particular ship type is expected to be operating its propulsion plant, and, when the ship is underway, how much of the time is spent at various speeds (known as the operating profile). For this project, an operating profile was provided for each ship type. In order to project annual fuel costs resulting from a particular combination of propulsion components, one of the parameters needed is propulsive coefficient. Since the ship operating profiles were provided in two knot increments from two knots up to maximum speed, it was necessary to relate propulsive coefficient to ship speed for all propulsor types and PLL generated geometries. Thus, the need to parameterize off-design performance at maximum and cruise speeds discussed earlier swelled into a need to parameterize off-design propulsor performance over the entire speed range.

Using PLL to Predict Propeller Off-design Performance

Tools Available to Predict Propeller Off-design Performance

As a design tool, PLL is normally used to determine the optimum propeller geometry to satisfy a series of conditions imposed by the user. Its user interface is constructed to allow the user to vary the conditions prescribed and assess the resulting impact on optimum propeller geometry. The need, at this point in the project however, was to parameterize the off-design performance of propellers for which the optimum geometry had already been determined, a task for which PLL was not expressly designed.

When designing propellers using computational methods, after PLL is used to define the preliminary performance and geometric characteristics of a propeller, other computer modelling tools are employed to further define the propeller geometry (in particular, accounting for blade skew and camber which are not accounted for within the lifting line analysis of PLL) and then analyze the steady and unsteady flow performance. The steady and unsteady performance analysis tools involve subdividing the propulsor into small panels and then predicting and analyzing the potential flow around the propeller blades (and/or ducts, stators) constructed of these small panel surfaces (appropriately known as panel method analysis).

While panel methods are extremely flexible in accommodating analysis of complex propulsor geometries, these methods require that large numbers of panels be used to accurately predict performance, which translates into large numbers of computations requiring substantial computer time.[15] As such, these tools were created for use in more detailed analysis of specific propeller geometries, and would have required a substantial time investment to have produced useful results for the variety of potential propulsor geometries studied in this project.

Using PLL to Predict Off-design Performance of Propellers with Fixed Pitch

Since the use of standard computer tools for off-design performance modelling did not appear feasible within the time frame available, a study of adapting PLL to the task was begun. Through a series of trial-and-error runs in PLL, a repeatable method to use PLL to predict off-design performance was devised. This method involved:

- selecting an optimum propeller geometry as predicted by PLL during a design condition run; typically this was most easily done by repeating the design run using PLL so that the chord lengths predicted by PLL reproduced the design expanded area ratio and pitch-to-diameter ratio,
- using the PLL option to update the blade geometry within PLL with the chord lengths just calculated,
- turning off the PLL chord length optimizing scheme and fixing the expanded area ratio to the design value,
- changing the ship speed used by PLL to the speed of interest,
- inputting a guess for the advance coefficient at the new speed, and the thrust required for the ship type at the new speed (based on the speed-power curve), and
- determining if the pitch-to-diameter ratio output by PLL matched the design pitch-to-diameter ratio.

If the pitch-to-diameter ratios did not match, the procedure was repeated using a different guess for advance coefficient. This process was repeated until the pitch-to-diameter ratios matched, at which point the advance coefficient and efficiency were recorded for that propeller geometry and ship speed.

For each propeller geometry chosen (three different propeller geometries representing the range of possible thrust coefficients for each type of propulsor were chosen), this process was repeated at four different ship speeds. The results of these PLL runs are presented graphically in Appendix 6 for the destroyer propellers, Appendix 7 for the amphibious ship propellers and Appendix 8 for the submarine propellers. The graphs depict the propulsive coefficient versus ship speed for the different types of propulsors, and each graph includes plots of the off-design performance of the three propeller geometries associated with different thrust coefficients at the design conditions.

From the graphs in these appendices it was clear that the relationship between efficiency, ship speed and propeller geometry could be predicted by fitting a surface to the three curves on each graph. This relationship would provide a means to predict the efficiency of propellers operating within the speed and geometry ranges for which PLL data had been gathered. Using this approach, polynomials relating speed to efficiency were fitted to each of the curves plotted in these appendices. The coefficients in these polynomials were then fitted with separate polynomials which resulted in equations relating ship speed and propeller geometry (expanded area ratio of the propeller at design conditions) to open water efficiency. As will be shown later, these correlations can be easily programmed so that once a propeller design has been chosen (as described in chapter two), its off-design performance can be predicted.

Predicting Off-design Performance for Controllable Pitch Propellers

Propellers for which the blade pitch can be varied during operation (controllable reversible pitch - CRP) have generally been used to provide satisfactory slow speed and reversing capability in combination with marine engines which operate in only one direction of rotation (gas turbines and diesels). These propellers have two characteristics which distinguish their off-design performance from similar propellers with fixed pitch blades:

- pitch changes at slow speeds (up to the speed where the changing pitch rather than engine speed is used to control ship speed) adversely affect the propeller efficiency, and
- CRP propeller hubs are larger than hubs of similar fixed pitch propellers, which adversely affects propeller efficiency at all speeds.

The affects of these characteristics on efficiency can be significant and therefore were taken into account by correcting fixed pitch propeller off-design performance to produce CRP off-design performance.

In naval ship applications using CRP propellers, ship speed is controlled by varying propeller pitch from zero percent at zero knots to one hundred percent at about twelve knots. To accelerate from less than twelve knots, the propeller rotational speed is held constant and the pitch is varied in such a manner so that the blade angle of attack is altered to make the propeller more efficient. This change in efficiency increases the thrust developed by the propeller, which causes the ship to accelerate. From this description, it is evident that a relationship must exist between efficiency and ship speed during the time that pitch control is used for speed control.

To determine the pattern of propeller efficiency change during varying pitch operation, a short computer program was written. For a particular ship type, the thrust versus speed curve was determined so that the propeller thrust coefficient, K_T, could be solved for at each speed. For marine engines, idle speeds range from 900 to 1200 rpm, and by assuming a typical naval ship gear ratio, propeller rpm and advance coefficient (J) may be calculated. With K_T and J known for ship speeds between 0 and 12 knots, the Wageningen B-series propeller polynomial was iteratively solved for the changing pitch-to-diameter ratio and propeller torque coefficient, K_Q, over the speed range of interest. Propeller efficiency at each speed, v, was then calculated using the relationship

$$\eta_o(v) = (K_T(v) * J(v)) \;/\; (2 * \pi * K_Q(v)).$$

The efficiency versus speed relationships for several different displacements of the destroyer ship type were calculated in this manner. Plots were made depicting the efficiency versus speed relationship for destroyers of three different displacements. It was noted from these plots that the shape of the curve was very similar for all three.

In an effort to further simplify the correlation, the efficiencies were normalized using the 12 knot efficiency; that is

$$\eta_{o(normalized)}(v) = \eta_o(v) \;/\; \eta_o(v{=}12\text{ kts}).$$

The normalized efficiencies for the three destroyer displacements were plotted on a graph in Appendix 9, and since there was no apparent difference between the three curves, a curve was fit to all the data. This curve can be used to characterize the pitch-varying performance of a CRP propeller by solving the equation for normalized efficiency at the desired speed and then multiplying the result by the open water efficiency at twelve knots.

The second unique characteristic of CRP off-design performance is the reduced efficiency which results from the larger than normal hub. A portion of the pitch varying apparatus is housed within the propeller and hub, forcing the hub size to be somewhat larger than a similar propeller with fixed pitch blades. For example, the typical hub size of a fixed pitch propeller is 20 percent of the propeller diameter. On the other hand, recent naval ship CRP propellers have hub sizes around 30 percent of the propeller. The reduction in blade area due to the larger hub results in an efficiency penalty for the CRP design. In 1967, Koning proposed the following efficiency correction factor for CRP propellers:

$$\eta_{o(CRP)} = \{\eta_{o(fixed)} * [1 - (D_{hub}/D_{prop})^2]\} \ / \ 0.96 \ .$$

In a later study, Baker verified the accuracy of this relationship.[16] Thus, if the CRP hub diameter (D_{hub}) is 20 percent of the diameter, the correction factor is one and the fixed pitch efficiency is returned. For the recent naval ship CRP propeller designs mentioned above, $\eta_{o(CRP)} = 0.948 * \eta_{o(fixed)}$, so the efficiency penalty due to the larger hub is 5.2 percent.

To account for the two affects described above, CRP propeller efficiency versus speed correlations describing off-design performance were derived from the fixed pitch propeller correlations. Whereas the fixed pitch efficiency between 0 and 12 knots is nearly constant, the equation describing efficiency versus speed during pitch changes was substituted for the CRP propeller correlations over this speed range. To account for the efficiency penalty associated with the larger hub, it was assumed that the hub diameter would be 30 percent of the propeller diameter, so 5.2 percent efficiency was subtracted from the fixed pitch correlations at all speeds to correct the correlations for predicting CRP propeller off-design performance. With the completion of this work, realistic performance correlations existed for all propeller types of interest.

Chapter Four

Impact of Propulsor Selection on Propulsion Group Volume and Weight

The type of propulsors selected to propel a ship directly affects the ship's performance characteristics, and can, as a result, affect the ship's acquisition and annual operating costs. Choosing an efficient propulsor type over one that is less efficient may mean that less powerful and less costly engines can be used in the design. Incorporating more efficient propulsors into a ship design can also lead to significantly reduced annual fuel costs as a result of being able to operate the engines at lower power levels over the entire speed operating profile. From these examples, it might be concluded that the optimum propulsor type for any ship design is the most efficient one; however, other factors associated with the potential impact of propulsor selection on the ship design must also be taken into consideration to assure that the propulsor type of choice is the "best" from a systems engineering standpoint.

Two of the more important characteristics of any marine system or component being considered for inclusion in a ship design are weight and volume of that system/component. These parameters are important from a naval architecture viewpoint not only because of the direct impact that a system's weight and volume have on the design, but also because these two parameters often have indirect, cascading effects on the design. For example, if a new component weighs more than the component it replaces, the ship's structural support in the vicinity of the new component might require strengthening. Depending on how much more the new component weighs, the weight of the structural improvements could cause the final installation weight of the new component to be significantly higher than the old component weight. Similarly, if a new component requires more volume than an existing component, providing the additional room to accommodate the new component will also tend to increase the final installation weight.

Applying this concern to propulsor selection, multiple component propulsor weighs more than a simple, single propeller and the cascading affect of the additional weight will tend to escalate acquisition costs of a ship designed with multiple component propulsors. While multiple component propellers tend to be more efficient, the effects of more weight on the total ship design can somewhat offset the efficiency gains. So, while at first the most efficient propulsor type may seem to be the best choice in all cases, weight and volume attributes of the propulsor type under consideration must also be accounted for within a tradeoff assessment.

As discussed in chapter one, the method to be used in this project to account for weight and volume variations resulting from selection of different propulsion plant components is to:

- determine the performance of a baseline ship using the propulsion plant components selected,
- determine the size and weight of those components,
- account for the differences in propulsion component size and weight between the baseline ship and the components chosen by adjusting the size of a geometrically similar (either larger or smaller) hull to envelope the payload and power plant, and
- repeat these steps until the propulsion plant power, size and weight are adjusted to match a final hull form which meets the specified performance criteria with the minimum displacement.

Since the propeller diameter for each ship type is known, equations correlating propeller diameter to weight may be used to predict weights of the various propeller types. The following propeller weight correlations were reported in papers written by Ingalls Shipbuilding and Bird-Johnson Company[17]:

For fixed pitch single propellers - $W_{FP} = 8.4D_P^3$,lb

For controllable, reversible pitch propellers - $W_{CRP} = 13.8D_P^3$,lb

For pitch control equipment associated

with CRP propellers - $W_{CTL} = 0.25W_{CRP}$,lb

For contrarotating propellers - $W_{CONTRA} = 12.0D_P^3$,lb .

Since propeller/stator combinations are expected to weigh nearly the same as contrarotating propellers, the contrarotating propeller correlation has been applied to these propulsors also. Duct weights can be predicted by calculating the weight of a steel cylinder having the dimensions used for the ducts analyzed for with PLL. From those dimensions $W_{DUCT} = 5.78D_P^3$,lb.

Of the propeller types included in this study, only the controllable reversible pitch propellers have an impact on ship hull volume. Internal volume must be reserved for the pitch control systems associated with these propellers. Based on the pitch control equipment installed on DDG-51, approximately 800 cubic feet should be reserved for each CRP propeller pitch control system.

These correlations provide the means to computer program the weight and volume impact of the various propellers studied in this project.

Chapter Five

The Application of Waterjet Propulsion to Large Surface Combatants

In 1980, a Swedish manufacturer, *KaMeWa*, who at the time was widely known for the design and manufacturing of controllable pitch propellers, introduced a new high-performance waterjet marine propulsion system into the market. The basic principle of this new propulsor is similar to propeller propulsion in that thrust is created by adding momentum to the water by accelerating it toward the stern of the vessel. Unlike a propeller however, a waterjet unit is located within the hull, requiring specially designed inlet ducting to channel the inlet flow efficiently into the unit's pump. The pump discharge is then directed through the jet nozzle located at the ship's transom, and the unit outflow is discharged into the atmosphere near the vessel's waterline. A diagram depicting a typical *KaMeWa* waterjet is provided in Figure 5.1.[18]

In less than a decade, these propulsors were in service in more than 225 vessels, including many small naval craft.[19] While the largest ship using waterjet propulsion thus far is 1000 tons in displacement, *KaMeWa* has studied the application of their waterjets to propel a 380 foot frigate design and a 530 foot, 8,100 ton destroyer design. The waterjet units designed for these applications are capable of providing up to 44,250 horsepower per unit. Performance of these units has been predicted by *KaMeWa* using a design program which matches data from scale model jet unit testing in the *KaMeWa* free-surface cavitation tunnel with scale model hull resistance and performance data for the vessel of interest. Based upon actual performance data gathered for smaller in-service units, *KaMeWa* projects that their jet design program predicts actual performance within ± two percent.[20]

The waterjet installations studied early in this project included combinations of 2, 4, 6 and 8 waterjet units per hull for the surface ship designs. After reviewing the dimensions of the waterjet units provided by *KaMeWa* for each of these combinations, all but the twin waterjet variants were felt to be impractical. According to the manufacturer, it is necessary to install the jet units in the transom, and, as a result, the arrangeable area in the sterns of the 4, 6 and 8 jet variants was mostly consumed by the propulsion system. In the destroyer design, this interfered with area required for the towed array sonar system and torpedo decoy system which were included in the prescribed fixed payload. In the amphibious ship design, little area near the waterline at the transom is available for jet installation due to the requirement to allow for a large, lowerable stern gate which provides access to the floodable well deck in the aft portion of the vessel. For these reasons, only twin waterjet configurations were evaluated beyond the preliminary stage of the project.

Waterjet Performance

Once the scope was narrowed to only practical designs, *KaMeWa* was provided with bare hull speed-power curves for destroyers of three different displacements, representing the range of expected ship designs under consideration. Using this information, *KaMeWa* provided predictions of ship speed versus propulsive coefficient and ship speed versus pump shaft rpm for each ship. The information which they provided characterized the performance of their twin Model 250 SII jet propulsion units, which they projected to be capable of developing 57,000 horsepower each in this ship design. Graphs depicting these relationships for the three ship displacements are provided in Appendix 10.

As evidenced in these graphs, the performance of this waterjet configuration was only slightly influenced by the displacements of the ships for which data was obtained. Since the variation of these data is small, and since the data represent the extremes of possible ship displacements, it was decided to fit the data with one curve representing the propulsive coefficient versus ship speed relationship, and one curve representing the pump speed versus ship speed relationship. These two correlations serve to characterize waterjet performance in the destroyer design.

Waterjet Weight and Volume Impact on Ship Design

As mentioned earlier, a key difference between propellers and waterjets is that waterjet propulsion units are located within the hull. According to *KaMeWa*, advantages to the waterjet arrangement include

- reduced hydroacoustic noise,
- reduced magnetic signature,
- reduced inboard noise and vibration levels, and
- protection of propulsors from damage, particularly in shallow waters.[21]

The main drawback resulting from this arrangement is that the waterjets take up internal hull volume and area near the stern that normally is devoted to the steering system and items in the payload (as discussed earlier in this chapter). The loss of volume for the steering system is of no consequence, since the waterjet propulsors include steerable nozzles which are advertised to produce steering forces larger in magnitude than rudders, thus obviating the need for a conventional steering system. On the other hand, the loss of arrangeable area/volume which adversely impacts carrying certain payload items may preclude some waterjet configurations from being used.

In any case, the volume and weight requirements of waterjets must be accounted for in a manner similar to the technique described for propeller weight and volume. Since all practical waterjet configurations involved *KaMeWa* Model 250 SII propulsion units, the weight and volume parameters for these units were obtained from the manufacturer. For the destroyer, these parameters per waterjet unit are

Dry weight including hydraulic controls -	77.55 Long Tons (LT)
Weight of water in inlet -	62.10 LT
Volume -	12,897 ft^3 .

For the amphibious ship, these parameters per waterjet unit are

Dry weight including hydraulic controls -	75.39 LT
Weight of water in inlet -	62.26 LT
Volume -	12,897 ft^3 .

Additionally, *KaMeWa* indicates that the size and weight of the controls for each unit are similar to the controls of a CRP propeller of similar size.(22) For these units, the controls would weigh about 6.80 LT per unit and would require an additional 800 ft^3 per unit.

To account for the waterjets' steering capabilities, which would eliminate the need for rudders and a steering system, the weight and volume requirements for this equipment should be subtracted from the numbers shown above. Typical values for steering system weight and volume for these size ships are 54 long tons and 3910 ft^3. For a twin waterjet design, then, the total weight addition (waterjets minus rudders and steering system) would be 238.9 LT for a destroyer, and 234.9 LT for the amphibious ship. The internal volume required would be 9787 ft^3 for either ship type.

Chapter Six

An Outline of the Propulsion Plant Component Assessment Computer Model

In the preceding chapters, it was shown that the propulsor performance, size and weight characteristics could be described for the three ship types being studied using a collection of polynomial equations. During the discussions of the efforts made to generate these correlations, the reasoning for parameterizing this particular collection of relationships was presented. When this project was begun, the logic path to be followed for combining various propulsion plant components in different combinations to produce viable propulsion systems was coarsely outlined. Within this outline, variables were separated into those which would be user-defined, and those which required evaluation within the program. The outline also defined the interfaces between separate portions of the project, including which information needed to be passed across the interfaces.

As the project has progressed, the outline of the logic to be used in programming the propulsion component assessment has evolved as necessary to accommodate sharing additional information between the various portions of the model so that a stable, iterative process to match a particular propulsion plant with the correctly sized *geosim* ship could be employed. Prior to beginning a detailed discussion of the propulsor portion of this computer model, it is worthwhile to outline the entire logic path in its present form, as this should provide insight into how the propulsor module interfaces with the remainder of the program. The computer model for each ship type can be broken down into five phases

- allowing the user to select a combination of propulsion components,
- iteratively matching the resulting power plant to a geosim hull,
- calculating acquisition cost of the correctly sized power plant components,
- calculating annual operating costs based on the expected operating profile, and
- providing cost and performance information to the user to allow for fairly comparing different component combinations.

User Selection of Propulsion Components

In this phase of the program, the user is prompted to provide the number and type of propulsors, transmissions and engines. A distinction is made between number and type of engines used at cruise speed versus at maximum speed, and number of propulsors used for cruising (which allows evaluating the affects of trailing a shaft at cruise speed to conserve fuel).

Matching the Power Plant to the Geosim Ship

The maximum power per engine, maximum engine rpm and idle engine rpm are determined based upon the engine type selected by the user. Resistance of a baseline ship is calculated at the speed used to design the propulsors (29 knots for the destroyer, 23.25 knots for the amphibious ship and 27 knots for the submarine). Based on the propulsor type selected and the resistance at design speed, propulsor geometry is defined. Since maximum engine rpm is known and optimum propulsor rpm at high speed can be predicted for the propulsor geometry chosen, a gear ratio and transmission efficiency can be predicted and the maximum ship speed is then iteratively calculated.

Next, the fuel tankage (and weight) to meet the endurance range requirement at the specified cruise speed must be calculated. Hull resistance and propulsor efficiency at the cruise speed are determined, and engine power to reach cruise speed is calculated. Using the engines' specific fuel consumption at that operating power level, endurance fuel storage requirements are determined.

Weights and sizes of the propulsion plant components which were selected by the user are calculated and added to the weight and volume of fuel storage. These totals are compared to the weight and volume of the baseline propulsion configuration. The size and displacement of the ship is then adjusted up or down as necessary to account for the differences, while preserving a geometrically similar hull form. Finally, this process is iterated until the weight and volume changes for two successive iterations are small. At the conclusion of this iterative loop, the size and performance of the power plant has been matched with a correctly sized *geosim* hull.

Calculating the Acquisition Costs of the Power Plant

Procurement costs for various propulsion plant components are well known in some cases, and must be predicted in others. Once the type of components is selected, the performance required of those components and their weight and size are typically the parameters used to predict their cost. To predict the impact on acquisition cost resulting from a power plant's affect on ship structural weight, a weight cost estimating relationship (typically specified in dollars per ton of structural weight) is normally used. Together, these methods can be used to estimate the change in acquisition costs as a result of selecting a particular combination of power plant components compared to the acquisition cost of the baseline ship with its assumed power plant configuration.

Calculating Annual Operating Costs

The costs of operating a marine power plant over some time period are, for the most part, made up of the cost of fuel to operate for a prescribed amount of time at various power levels, the cost to maintain the components and the cost of paying people to operate the plant. Maintenance costs vary depending on the components comprising the power plant, and have been fairly accurately predicted. Likewise, manning costs are known and vary little except when specific skills are called for or the number of operators for a particular component combination is much higher or lower than the baseline. In general, these costs have increased in a stable pattern over the years, so that the present value of these costs 30 years from now can be predicted with reasonable accuracy.

Annual fuel usage can be predicted using an operating profile, which depicts the amount of time that a ship operates at each speed throughout its speed range while the ship is underway. Using this information, and knowing the efficiency of the power train, an estimate of the amount of time during a year that the ship's engines are operated at various power levels can be made. The fuel consumption rate at each power level multiplied by the amount of time spent at that power yields annual fuel consumption. By having a prediction for the amount of fuel consumed during a typical year, and an estimate of fuel prices, annual fuel costs can be estimated. Although fuel prices are relatively unstable, it must be assumed that the present value of fuel expenses at the end of a thirty year ship life can be accurately predicted to predict life cycle fuel costs. While this assumption may not be valid in predicting actual operating costs for budgeting purposes, any inaccuracies are equally applied to any propulsion combination being modelled, so that the results can be compared fairly between variant power plants.

Providing Cost and Performance Information

This phase of the program gathers information calculated in phases 2,3 and 4 and organizes it into the program's output. The cost and performance information produced enables the user to comparatively assess one combination of power plant components versus other power plant candidates using whichever criteria the user chooses.

Structure of the Propulsor Module

The propulsor module for each ship type was written in the C programming language and accomplishes three main objectives

- choose the optimum propulsor geometry at the cavitation design conditions based on the amount of thrust required to be developed by each propulsor,
- predict the propulsive coefficient (PC) and propulsor rpm versus speed characteristics for the chosen propulsor geometry, and
- calculate the weight and volume of the selected propulsor type.

For each ship type, a C function called "prop_design" selects the optimum propeller geometry, a second C function called "prop_performance" predicts the PC and propulsor rpm and a third C function called "prop_size" calculates weight and volume of the propulsor.

The Prop_Design Function

This function calculates the most efficient propeller geometry for the type of propeller selected using the thrust coefficient, C_T, versus efficiency relationship developed in chapter two. Since each point along those curves represents the efficiency of a different propeller geometry, equations relating C_T versus expanded area ratio (EAR) and C_T versus pitch-to-diameter ratio (PDR) yield the most efficient propeller geometry which produces the required amount of thrust while showing satisfactory cavitation performance.

To predict the optimum geometry, this function takes as information provided to it

- number of propulsors generating thrust at the design conditions,
- type of propulsors in the design being evaluated, and
- hull resistance at the design speed.

Using this information, the function calculates C_T and evaluates the correlations predicting EAR and PDR versus C_T for the type of propeller chosen. This function returns the values for EAR and PDR to the main program for use by the "prop_performance" function.

Since the type of waterjets shown to be viable for the surface ships was limited to only one *KaMeWa* model, there is no need for this function address waterjet selection. For the amphibious ship, this function is limited to calculating the geometry for single fixed pitch and CRP propeller types. For the destroyer, propeller geometry may be calculated for ducted or non-ducted versions of fixed pitch, CRP and contrarotating propellers, and fixed pitch propellers with pre-swirl stators. Copies of the amphibious ship and destroyer "prop_design" functions are provided in Appendix 11.

The Prop_Performance Function

This function calculates propulsor performance versus speed for a selected propulsor type and geometry. For propellers, the function takes as input

- the type of propeller selected,
- the number of propellers in use at maximum speed,
- the number of propellers in use at cruise speed,
- the idle ship speed (ship speed when the engines are idling and CRP propellers are still at full pitch; this speed marks the point below which ship speed is controlled by varying propeller blade pitch),
- the expanded area ratio and pitch-to-diameter ratio of the optimum propeller design calculated by the function "prop_design", and
- the speed for which the propulsive coefficient is desired to be known.

Using this information and the off-design ship speed versus efficiency and ship speed versus advance coefficient correlations discussed in chapter three, the function calculates propulsive coefficient and propeller rpm of the propeller type selected at the chosen ship speed.

In order to calculate propulsive coefficient for the propellers, a value for the hull efficiency for each ship type was needed. Hull efficiency is defined as

$$\eta_{hull} = (1-t) / (1-w) .$$

For the amphibious ship, the thrust deduction factor, t, was assumed to be 0.095, which is typical for the amphibious ship hull form. The wake fraction was calculated by PLL to be 0.035, which is also typical for this ship type. These values resulted in a hull efficiency for the amphibious ship of 0.9378. For the destroyer, t = 0.065 and w = 0.026, which yielded a hull efficiency of 0.9702. The accuracy of these values for hull efficiency was verified by consulting several

David Taylor model basin reports for similar ships. Since relative rotative efficiency of PLL designed propellers is accounted for by PLL, only the hull efficiencies are used within "prop_performance" to convert propeller efficiency to propulsive coefficient. Since *KaMeWa* provided propulsive coefficient versus speed data for the waterjets, the correlations developed from these data are already adjusted for hull efficiency.

Figures 6.1 and 6.2 provide plots of "prop_performance" output for the amphibious ship propulsors and destroyer propulsors respectively. These plots were created by using "prop_performance" to calculate propulsive coefficients at the cavitation design speed for several different ship displacements (represented by differing thrust coefficients, C_T). From these figures, the comparative values of PC predicted for the various propulsor types appear to be consistent with expected results.

When calculating propeller rpm within "prop_performance", it was necessary to assume propeller diameters for the ship types. Since the amphibious ship design presently being studied is expected to have a propeller diameter of 16 feet, this is the propeller diameter which "prop_performance" uses to calculate propeller rpm from the ship speed versus advance coefficient relationship. For the twin screw destroyer, the DDG-51 propeller diameter of 17 feet is used. For a 3

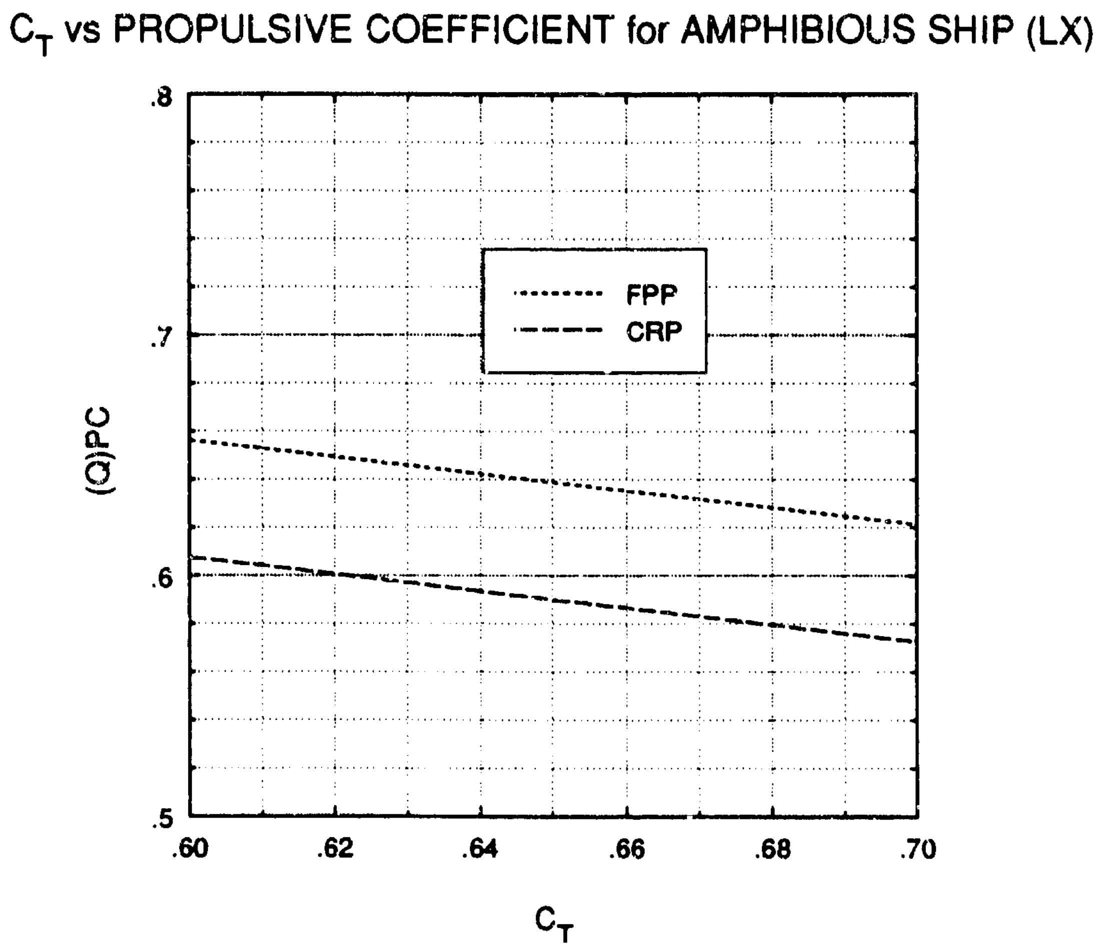


Figure 6.1: Amphibious ship propulsive coefficient vs thrust coefficient, C_T.

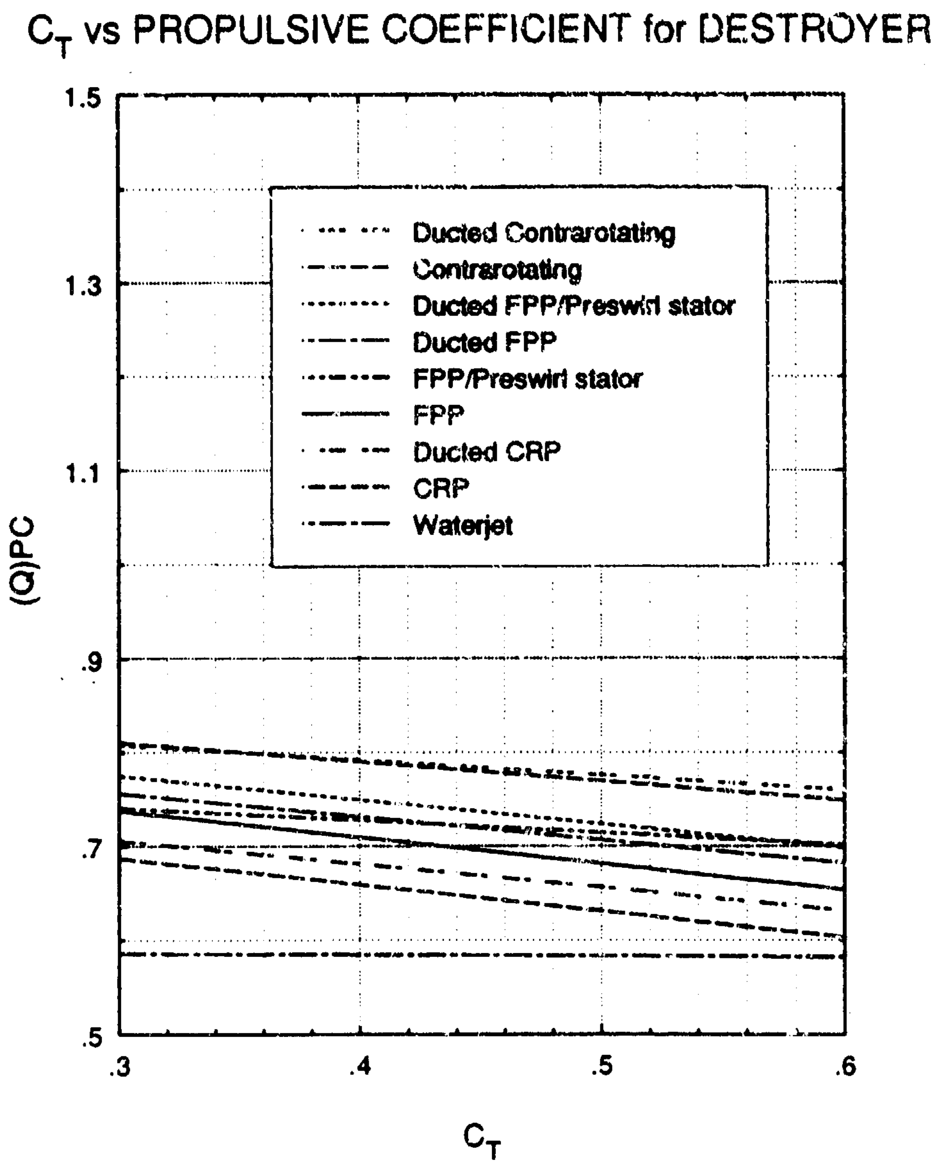


Figure 6.2: Destroyer propulsive coefficient vs thrust coefficient, C_T.

screw destroyer, a propeller diameter of 15.2 feet is assumed (justification for this assumption is provided in Appendix 12).

As mentioned earlier, one of the inputs which "prop_performance" requires to predict CRP propeller performance is the ship speed when the propellers reach full pitch. This speed is calculated by a separate C function entitled "crp_idle". Within "crp_idle" the values for maximum engine rpm and maximum propeller rpm are used to calculate a gear ratio. The gear ratio is used with idle engine rpm to calculate the idle propeller rpm. Then, using the ship speed versus advance coefficient correlations, advance coefficient is calculated for the idle propeller rpm and, finally, ship speed at that rpm is solved for. At the speed calculated by "crp_idle", "prop_performance" switches from the constant rpm / varying pitch correlation to the constant pitch / varying rpm correlation.

Copies of the "prop_performance" and "crp_idle" functions for the destroyer and amphibious ship are provided in Appendix 13.

The Prop_Size Function

This function calculates the weight (and internal hull volume when applicable) of the selected propulsor type. If the propulsors selected are propellers, this function uses the weight (and volume) correlations for the various ducted and non-ducted propellers presented in chapter 4. If waterjets are the selected propulsors, the weights and volumes of the KaMeWa Model 250 SII discussed in chapter 5 are returned. A copy of the "prop_size" function which is applicable to either surface ship is provided in Appendix 14.

Chapter Seven

Conclusions

Choosing the "best" combination of propulsion plant components for a particular naval ship design is a complex task. This task is further complicated because the country's political and economic climate periodically redefines what "best" means when applied to design and purchase of a national asset. A computer program is being developed which will provide cost and performance data for naval ship propulsion plants, to assist the decision-makers in assessing different component combinations, using whichever criteria they choose.

Within that computer program, routines characterizing the performance, size and weight impacts of a variety of propulsors were needed. These routines have been written for up to nine different types of propulsors (eight propeller configurations and one waterjet configuration) for three ship types. The correlations for selecting optimum propeller geometry and predicting propeller performance invoked by these routines are the result of propeller computer modelling carried out using the Propeller Lifting Line (PLL) computer program, which was written at MIT for use in preliminary propeller design. PLL-designed propellers were filtered through cavitation criteria developed for each ship type, so that the propeller efficiencies predicted by these computer routines represent the performance of only those propellers having reasonable cavitation performance. Correlations describing the waterjet configuration were developed from information supplied by the waterjet manufacturer KaMeWa.

To ensure that the propulsor correlations were properly programmed, the routines were tested for each ship type over a range of displacements and speeds. They yield realistic predictions over a wide range of ship displacements and speeds which are consistent with known propulsor performance for the type of ship each is associated with.

Recommendations for Further Work

The ability to model propeller designs and predict performance using PLL was invaluable. Without this capability, the collection of data used to characterize propeller design and performance would have been limited for several of the propeller types of interest. As stated in chapter two however, PLL was designed to be a preliminary design tool, and other methods are available to predict more accurately the off-design propeller performance in steady and unsteady flow. A technique was developed to use PLL to predict off-design performance. While the data resulting from applying this technique are consistent with known propeller performance, the off-design performance information obtained by using PLL could be further verified by using the steady flow panel methods of the Propeller Steady Flow (PSF) program. Similarly, evaluating the cavitation performance of PLL designs using Burrill's criterion could be further validated by using the unsteady flow panel methods of the Propeller Unsteady Flow (PUF) computer program. While PSF and PUF programs do not exist for all propeller configurations included in this project, those that do exist could be used to validate the PLL methods described herein.

Prior to this project, PLL had not been used to compare such a wide range of potential propeller configurations for the same ship application. Additionally, corroboration of PLL output with the Burrill cavitation criterion had not been done. As a result, two suggested changes to the PLL user interface arose during this effort:

- an item should be added to PLL's main menu which allows the user to change the hub centerline depth. Presently, if the same propeller is being studied for use on two ships of different displacement (affecting hub centerline depth), PLL must be exited and then reentered using a new input file.
- since the Burrill cavitation criterion is widely accepted, the non-dimensional thrust factor, τ_c, used by Burrill could be calculated and provided in the PLL output summary.

References

(1) Rains, Dean A. and John A. Johnson. "Cruiser, Destroyer, Frigate Technology Assessments", *American Society of Naval Engineers Symposium*, 1990, p.142.

(2) Ibid.

(3) Kerwin, Justin E. and David P. Keenan. "Computational Aspects of Propulsor Design", Presented at *Marine Computers '91, The 2nd Symposium on Computer Applications in the Marine Industry*, SNAME New England Section, Boston, MA, September 1991.

(4) Schlappi, Herman C. "An Innovative Energy Saving Propulsion System for Navy Ships", *Naval Engineer's Journal*, April 1982.

(5) Kerwin and Keenan. "Computational Aspects of Propulsor Design".

(6) Coney, W. B. *A Method for the Design of a Class of Optimum Marine Propulsors*. PhD thesis, Department of Ocean Engineering, Massachusetts Institute of Technology, August 1989.

(7) Hsin, C. - Y. Efficient *Computational Methods for Multi-Component Lifting Line Calculations*. Master's thesis, Department of Ocean Engineering, Massachusetts Institute of Technology, 1986.

(8) Kerwin, J. E., W. B. Coney and C. - Y. Hsin. "Optimum Circulation Distributions for Single and Multi-component Propulsors", *Twenty-first American Towing Tank Conference*, 1986, pp. 53-62.

(9) Kerwin, J. E., W. B. Coney and C. - Y. Hsin. "Hydrodynamic Aspects of Propeller/Stator Design", *Proceedings of the Society of Naval Architects and Marine Engineers Propellers '88 Symposium*, Virginia Beach, VA, September 1988.

(10) Coney, William B. *MIT-PLL User's Manual.* Department of Ocean Engineering, Massachusetts Institute of Technology, November 1988.

(11) Ibid.

(12) Coney. *A Method for the Design of a Class of Optimum Marine Propulsors.*

(13) Comstock, J. P., editor. *Principles of Naval Architecture*, Society of Naval Architects and Marine Engineers, 1967, p. 408.

(14) Harvald, SV. AA. *Resistance and Propulsion of Ships* John Wiley and Sons, New York, 1983, P. 218.

(15) Kerwin and Keenan. "Computational Aspects of Propulsor Design".

(16) Wind, Jaap. "Hub Size Selection Criteria for Controllable Reversible Pitch Propellers as a Means to Ensure System Integrity", *Naval Engineer's Journal*, December 1978.

(17) *Advanced Ship Synthesis Evaluation Tool (ASSET) User's Manual*, David Taylor Naval Ship Research and Development Center, Volume 2C, Weight Module.

(18) Svensson, Rolf. "The KaMeWa Water-jet Propulsion System", *Maritime Defence*, December 1987, pp. 427-436.

(19) Svensson, Rolf. "Water Jet Propulsion of Large Naval Craft", *American Society of Naval Engineers Symposium*, 1990, pp. 24-43.

(20) Ibid.

(21) Svensson. "The KaMeWa Water-jet Propulsion System".

(22) Ibid.

Appendix One

PLL Wake Files

The following files were created to describe the wake velocity fields at the propeller inflow for a destroyer, an amphibious ship and a submarine. The destroyer and amphibious ship files were created from wake velocity data provided by David Taylor Model Basin for DDG-51 and LSD-49, respectively. The wake velocity data used to create the PLL submarine wake file was read from Figure A-1, which was taken from course notes for the Submarine Design Course taught during Professional Summer at MIT by Captain Harry Jackson, USN(Ret).

Destroyer Wake File

```
PROPELLER LIFTING LINE RUN: DDG        10 FEB 1992
********************* WAKE INPUT FILE *********************
NUMBER OF RADII FOR INPUTS: 6
NUMBER OF HARMONIC COEFFICIENTS (axial, radial, tangential): 7 3 2
NONDIMENSIONAL RADII FOR INPUTS:
0.4000 0.5000 0.6000 0.7000 0.8000 0.9000
AXIAL VELOCITY COSINE HARMONIC COEFFICIENTS:
0.9917  0.9908  0.9810  0.9721  0.9665  0.9657
-0.0373 -0.0222 -0.0169 -0.0151 -0.0140 -0.0152
-0.0212 -0.0135 -0.0082 -0.0050 -0.0024 -0.0009
-0.0083 -0.0051 -0.0020  0.0004  0.0029  0.0053
0.0015  0.0005  0.0014  0.0030  0.0039  0.0064
0.0044  0.0030  0.0034  0.0039  0.0033  0.0057
0.0051  0.0036  0.0036  0.0042  0.0036  0.0053
AXIAL VELOCITY SINE HARMONIC COEFFICIENTS:
0.0000  0.0000  0.0000  0.0000  0.0000  0.0000
```

-0.0257 -0.0155 -0.0142 -0.0168 -0.0192 -0.0198
-0.0251 -0.0175 -0.0140 -0.0137 -0.0148 -0.0156
-0.0244 -0.0159 -0.0106 -0.0089 -0.0089 -0.0087
-0.0169 -0.0108 -0.0065 -0.0051 -0.0032 -0.0026
-0.0100 -0.0045 -0.0016 -0.0020 -0.0010 -0.0011
-0.0016 -0.0012 0.0018 0.0006 -0.0003 0.0000

RADIAL VELOCITY COSINE HARMONIC COEFFICIENTS:
0.0036 0.0110 0.0088 0.0071 0.0040 -0.0029
0.0079 0.0066 0.0058 0.0053 0.0048 0.0027
0.0036 0.0054 0.0071 0.0061 0.0054 0.0050
RADIAL VELOCITY SINE HARMONIC COEFFICIENTS:
0.0000 0.0000 0.0000 0.0000 0.0000 0.0000
0.0057 0.0036 0.0013 0.0001 0.0048 -0.0046
0.0092 0.0091 0.0085 0.0082 0.0070 0.0058
TANGENTIAL VELOCITY COSINE HARMONIC COEFFICIENTS:
-0.0066 0.0128 0.0129 -0.0019 -0.0018 0.0063
-0.0077 -0.0027 -0.0024 0.0034 0.0053 0.0071
TANGENTIAL VELOCITY SINE HARMONIC COEFFICIENTS:
0.0000 0.0000 0.0000 0.0000 0.0000 0.0000
0.0104 -0.0007 -0.0008 0.0027 0.0022 -0.0033

Amphibious Ship Wake File

PROPELLER LIFTING LINE RUN: LSD 10 FEB 1992
********************* WAKE INPUT FILE *********************
NUMBER OF RADII FOR INPUTS: 6
NUMBER OF HARMONIC COEFFICIENTS (axial, radial, tangential): 7 0 7
NONDIMENSIONAL RADII FOR INPUTS:
0.4000 0.5000 0.6000 0.7000 0.8000 0.9000
AXIAL VELOCITY COSINE HARMONIC COEFFICIENTS:
1.0056 0.9906 0.9694 0.9595 0.9536 0.9428
-0.0113 -0.0215 -0.0366 -0.0479 -0.0578 -0.0658
0.0178 0.0102 0.0003 -0.0066 -0.0126 -0.0172
0.0128 0.0107 0.0062 0.0048 0.0026 0.0020
-0.0007 0.0030 0.0064 0.0088 0.0101 0.0107
-0.0078 0.0000 0.0070 0.0093 0.0091 0.0100
-0.0057 -0.0005 0.0062 0.0061 0.0048 0.0045
AXIAL VELOCITY SINE HARMONIC COEFFICIENTS:
0.0000 0.0000 0.0000 0.0000 0.0000 0.0000
0.0470 0.0379 0.0240 0.0257 0.0324 0.0358

0.0104 0.0119 0.0153 0.0189 0.0213 0.0238
-0.0122 -0.0039 0.0068 0.0111 0.0126 0.0126
-0.0189 -0.0140 -0.0038 0.0001 0.0016 0.0037
-0.0125 -0.0117 -0.0099 -0.0073 -0.0051 -0.0028
-0.0049 -0.0090 -0.0114 -0.0119 -0.0088 -0.0058
TANGENTIAL VELOCITY COSINE HARMONIC COEFFICIENTS:
0.0365 0.0191 0.0025 0.0085 0.0276 0.0299
0.0237 0.0029 0.0038 0.0010 -0.0032 -0.0055
0.0046 0.0010 -0.0022 -0.0020 -0.0018 -0.0012
0.0097 0.0050 0.0034 0.0010 0.0013 0.0011
0.0076 0.0075 0.0068 0.0041 0.0014 0.0001
0.0049 0.0059 0.0072 0.0065 0.0036 0.0015
0.0016 0.0048 0.0094 0.0071 0.0041 0.0020
TANGENTIAL VELOCITY SINE HARMONIC COEFFICIENTS:
0.0000 0.0000 0.0000 0.0000 0.0000 0.0000
0.0037 0.0008 -0.0054 -0.0075 -0.0077 -0.0096
0.0095 0.0059 0.0027 0.0012 0.0004 -0.0005
0.0068 0.0063 0.0066 0.0060 0.0041 0.0030
0.0008 0.0031 0.0061 0.0066 0.0037 0.0020
-0.0024 0.0006 0.0036 0.0044 0.0018 0.0015
-0.0002 0.0009 0.0020 0.0018 0.0014 0.0011

Submarine Wake File

PROPELLER LIFTING LINE RUN: SUBMARINE
********************** WAKE INPUT FILE *********************
NUMBER OF RADII FOR INPUTS: 9
NUMBER OF HARMONIC COEFFICIENTS (axial, radial, tangential): 1 0 0
NONDIMENSIONAL RADII FOR INPUTS:
0.2000 0.3000 0.4000 0.5000 0.6000 0.7000 0.8000 0.9000 1.0000
AXIAL COSINE HARMONIC COEFFICIENTS:
0.4600 0.4900 0.5100 0.5350 0.5800 0.6500 0.6900 0.7400 0.7900
AXIAL SINE COEFFICIENTS:
0. 0. 0. 0. 0. 0. 0.
0. 0.

Appendix Two

PLL Input Files

The following files are a sampling of the input files created for using PLL. Distinguishing features of the various files are noted where appropriate.

Input File for a 8300 ton Destroyer Fixed Pitch Propeller Design

PROPELLER LIFTING LINE RUN: OVERALL INPUT FILE
48.9230 .... Ship speed (ft/sec)
1.9905 .... Fluid density
15.2000 .... Shaft centerline depth (ft)
1 Number of components
N No image hub to be used
N No image duct to be used
N Component 1 is not a ringed propeller
5 Number of blades on component 1
17.0000 .... Diameter of component 1 (ft)
ddg.bld File containing blade inputs for comp. 1
17.0000 .... Diameter of wake for component 1
ddg.wak File containing wake inputs for component 1

Notes: 1) 29 knot ship speed input based on cavitation criteria for this ship type
2) Shaft centerline depth corresponds to 8300 ton displacement

Input File for a 9060 ton Destroyer Contrarotating Propeller Design

PROPELLER LIFTING LINE RUN: OVERALL INPUT FILE
48.9230 .... Ship speed (ft/sec)
1.9905 .... Fluid density
16.5200 .... Shaft centerline depth (ft)
2 Number of components
N No image hub to be used

N No image duct to be used
N Component 1 is not a ringed propeller
2.0000 .... Axial location of component 1 (ft)
5 Number of blades on component 1
17.0000 .... Diameter of component 1 (ft)
ddg.bld File containing blade inputs for comp. 1
17.0000 .... Diameter of wake for component 1
ddg.wak File containing wake inputs for component 1
N Component 2 is not a ringed propeller
-2.0000 .... Axial location of component 2 (ft)
5 Number of blades on component 2
17.0000 .... Diameter of component 2 (ft)
ddg.bld File containing blade inputs for comp. 2
17.0000 .... Diameter of wake for component 2
ddg.wak File containing wake inputs for component 2

Notes: 1) Contrarotating design specified through use of two components
2) Shaft centerline depth corresponds to 9060 ton destroyer

Input File for 8500 ton Destroyer Ducted Propeller/Pre-swirl Vane Combination

PROPELLER LIFTING LINE RUN: OVERALL INPUT FILE
48.9230 .... Ship speed (ft/sec)
1.9905 .... Fluid density
17.2500 .... Shaft centerline depth (ft)
2 Number of components
N No image hub to be used
Y Image duct to be used
0.5000 .... (Duct chord length)/(Component #1 diameter)
0.0085 .... Drag coefficient for the duct
0.0750 .... (Duct thickness)/(Component #1 diameter)
17.7500 .... Duct diameter (ft)
0. .... Axial location of duct mid-chord (ft)
2.0000 .... Axial location of component 1 (ft)
5 Number of blades on component 1
17.0000 .... Diameter of component 1 (ft)
ddg.bld File containing blade inputs for comp. 1
17.0000 .... Diameter of wake for component 1

ddg.wak File containing wake inputs for component 1
-2.0000 .... Axial location of component 2 (ft)
5 Number of blades on component 2
17.0000 .... Diameter of component 2 (ft)
ddg.bld File containing blade inputs for comp. 2
17.0000 .... Diameter of wake for component 2
ddg.wak File containing wake inputs for component 2

Notes: 1) Dimensions of the duct defined in this input file
2) Propeller/pre-swirl combination specified similarly to contrarotating propeller; when component rpm is input to be zero, PLL assumes that the component is a stator.

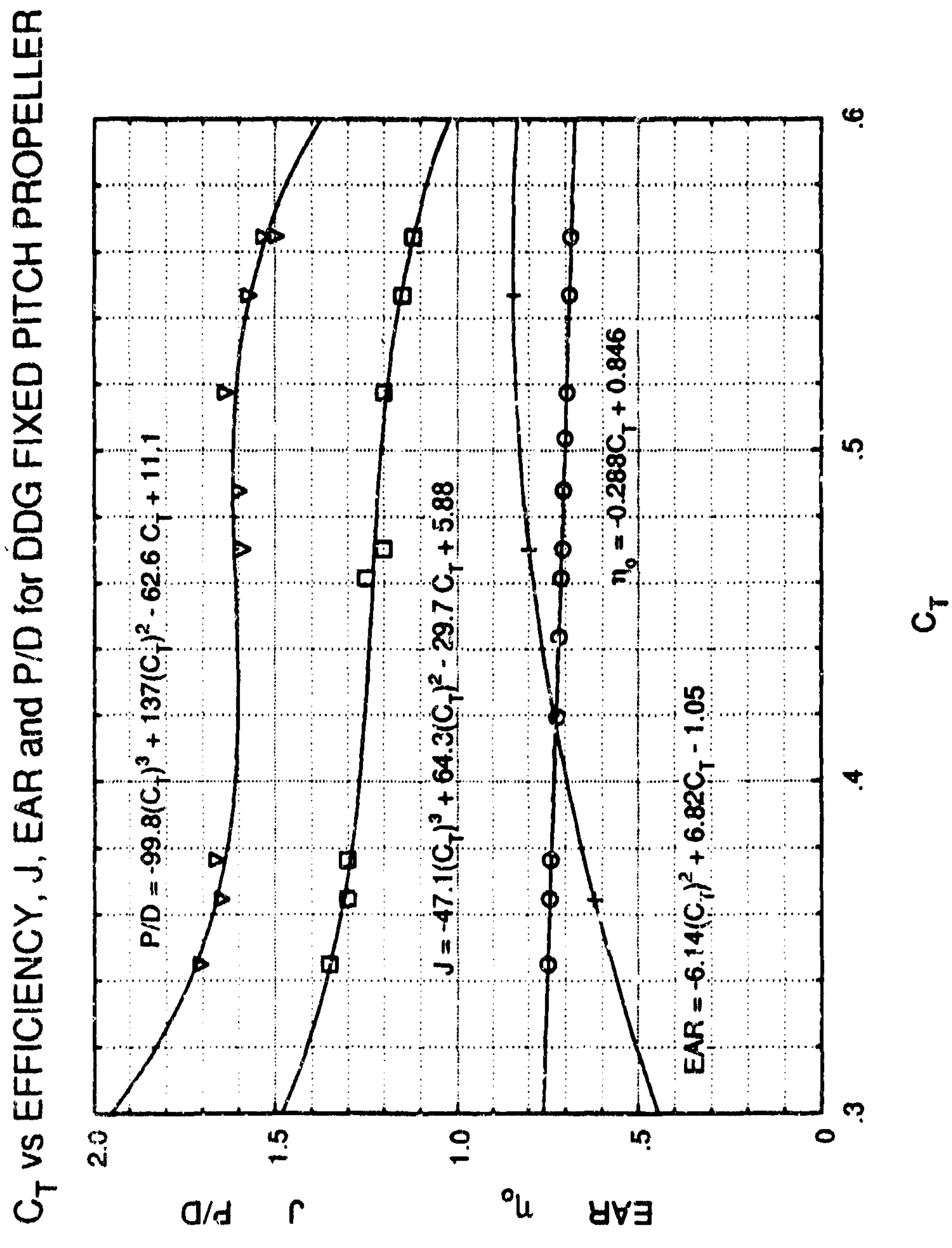
Input files for several displacements of each ship type were created, and differences between those files and the sample included here involved:

- specifying the correct cavitation design speed for the ship type,
- adjusting the shaft centerline depth for the displacement,
- choosing the correct number of propeller components,
- choosing the correct propeller diameter for the ship type, and
- specifying duct dimensions for ducted designs.

Appendix Three

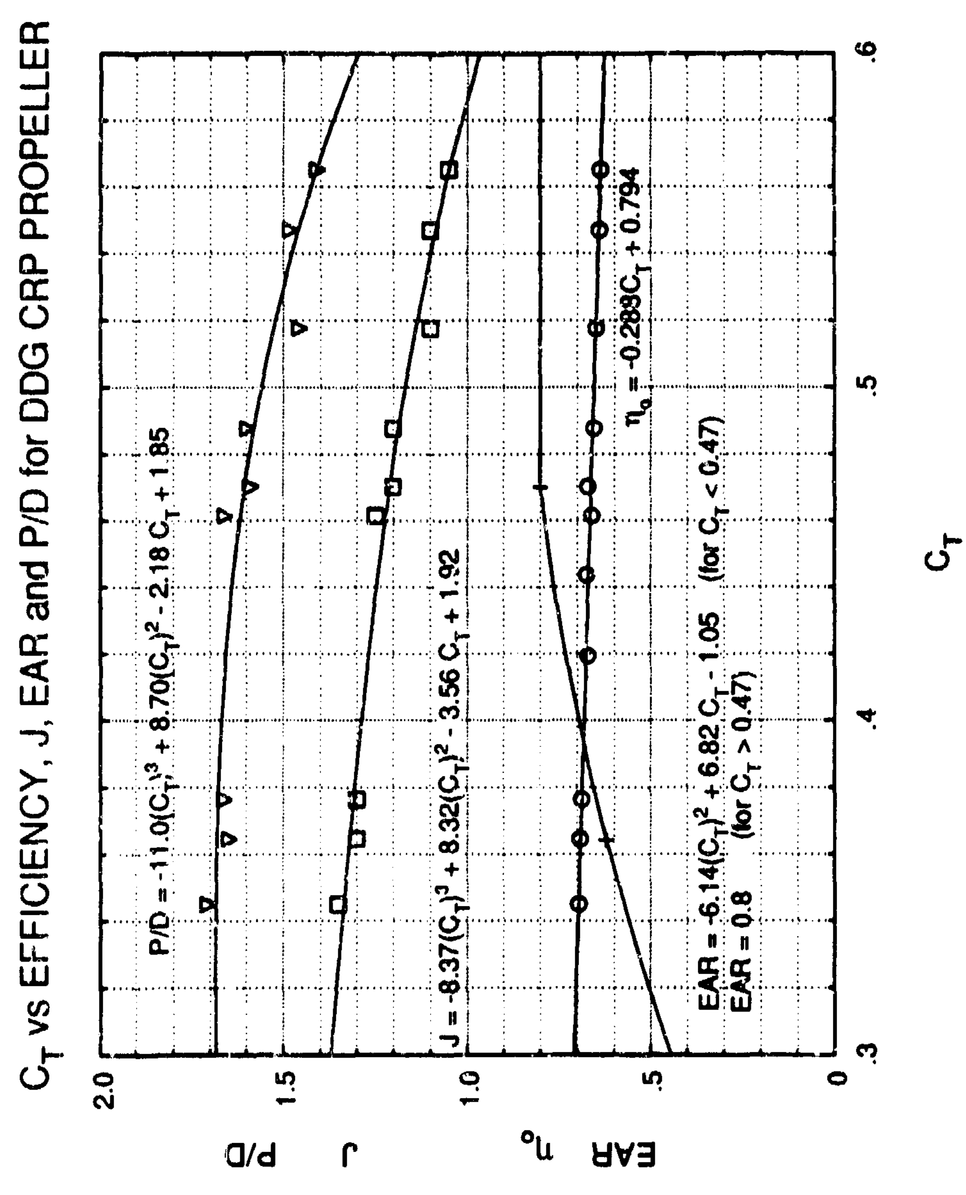
Destroyer Propeller Design Performance

Figures A3.1-A3.8 depict destroyer propeller open water efficiency versus thrust coefficient for the various propeller types considered during this project. All data in these figures represent propellers which satisfied the cavitation standard developed for the destroyer design (<20.7% back cavitation when evaluated using Burrill criterion at 29 knot ship speed). The thrust coefficients in these figures represent thrust at 29 knots.



CT vs EFFICIENCY, J, EAR and P/D for DDG FIXED PITCH PROPELLER
P/D = -99.8(CT)3 + 137(CT)2 - 62.6 CT + 11.1
J = -47.1(CT)3 + 64.3(CT)2 - 29.7 CT + 5.88
ηo = -0.288CT + 0.846
EAR = -6.14(CT)2 + 6.82CT - 1.05
P/D
J
ηo
EAR
CT
2.0
1.5
1.0
.5
0
.3
.4
.5
.6

Figure A3.1



C_T vs EFFICIENCY, J, EAR and P/D for DDG CRP PROPELLER
P/D = -11.0(C_T)^3 + 8.70(C_T)^2 - 2.18 C_T + 1.85
J = -8.37(C_T)^3 + 8.32(C_T)^2 - 3.56 C_T + 1.92
η_o = -0.283C_T + 0.794
EAR = -6.14(C_T)^2 + 6.82 C_T - 1.05 (for C_T < 0.47)
EAR = 0.8 (for C_T > 0.47)
P/D
J
η_o
EAR
C_T
2.0
1.5
1.0
.5
0
.3
.4
.5
.6

Figure A3.2

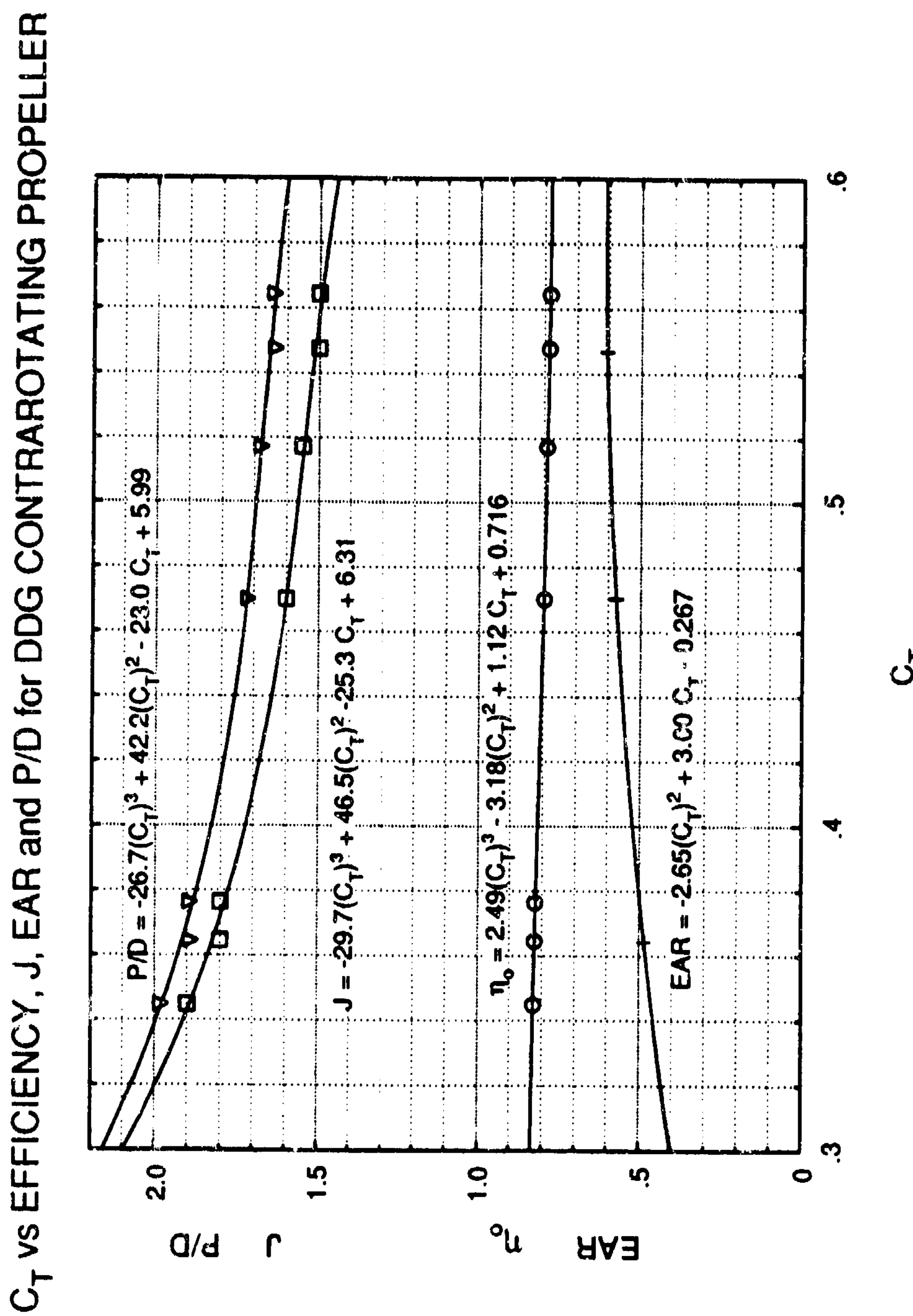

C_T vs EFFICIENCY, J, EAR and P/D for DDG CONTRAROTATING PROPELLER
P/D = -26.7(C_T)^3 + 42.2(C_T)^2 - 23.0 C_T + 5.99
J = -29.7(C_T)^3 + 46.5(C_T)^2 -25.3 C_T + 6.31
η_o = 2.49(C_T)^3 - 3.18(C_T)^2 + 1.12 C_T + 0.716
EAR = -2.65(C_T)^2 + 3.00 C_T - 0.267
P/D
J
η_o
EAR
2.0
1.5
1.0
.5
0
.3
.4
.5
.6
C_T

Figure A3.3

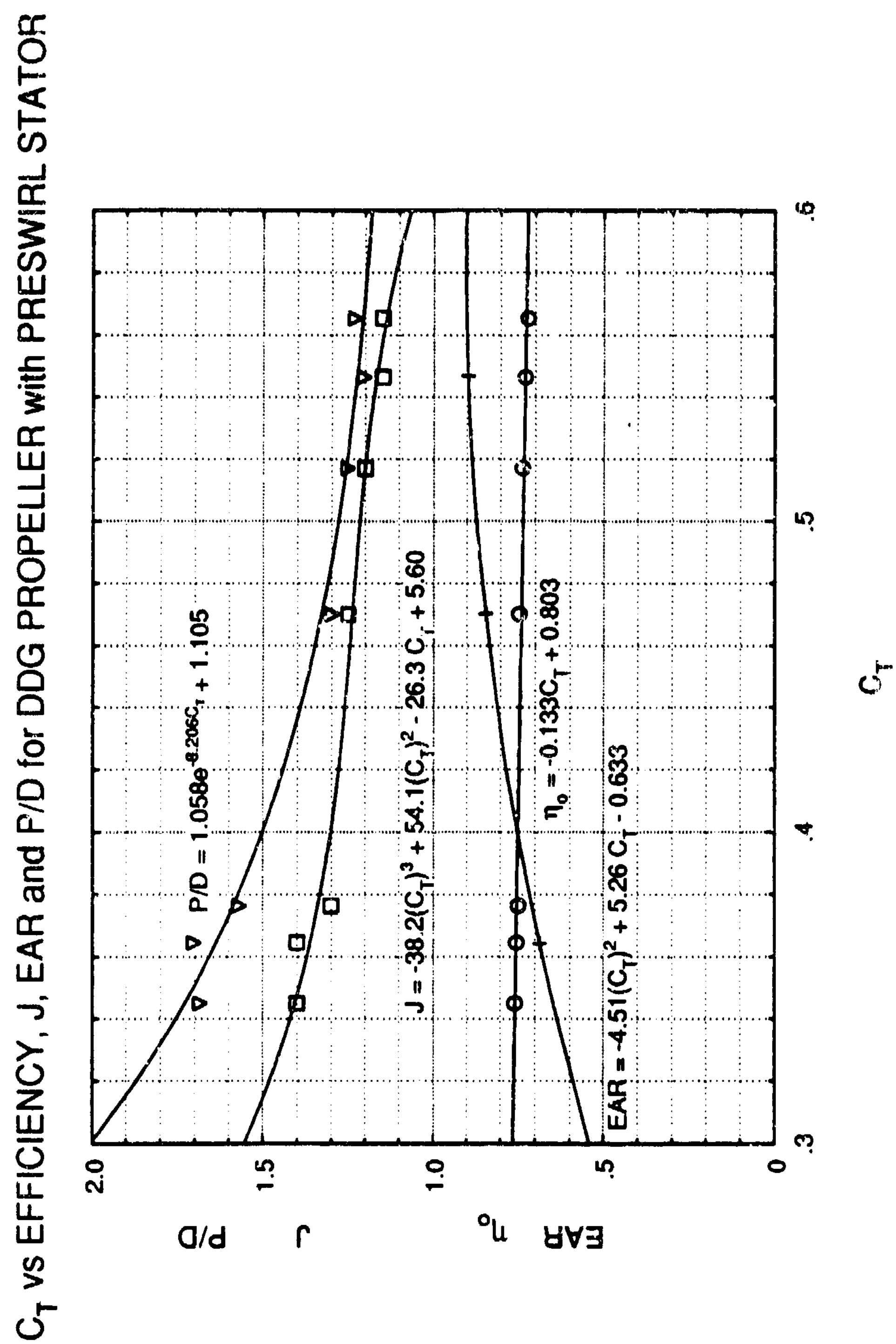
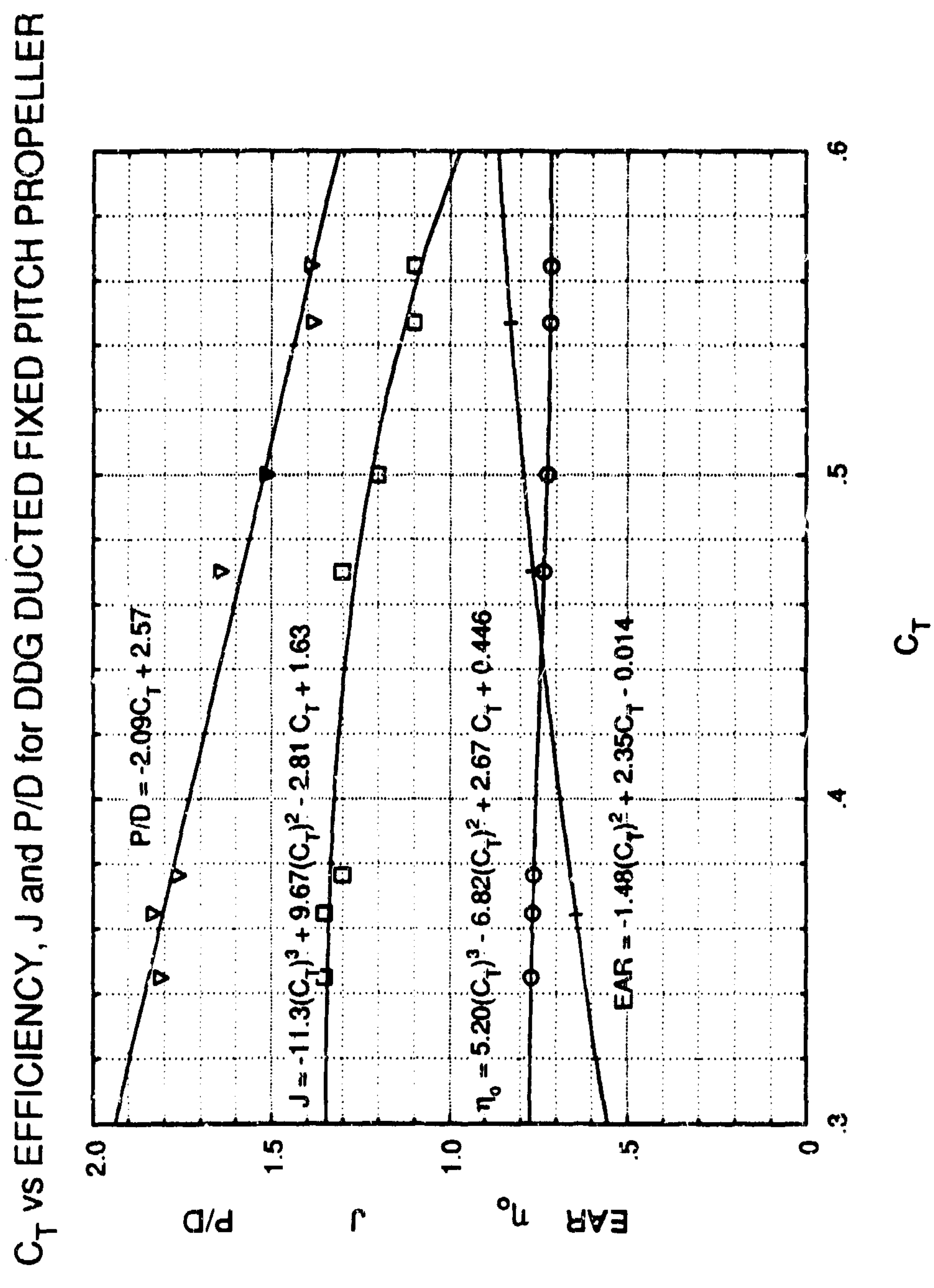
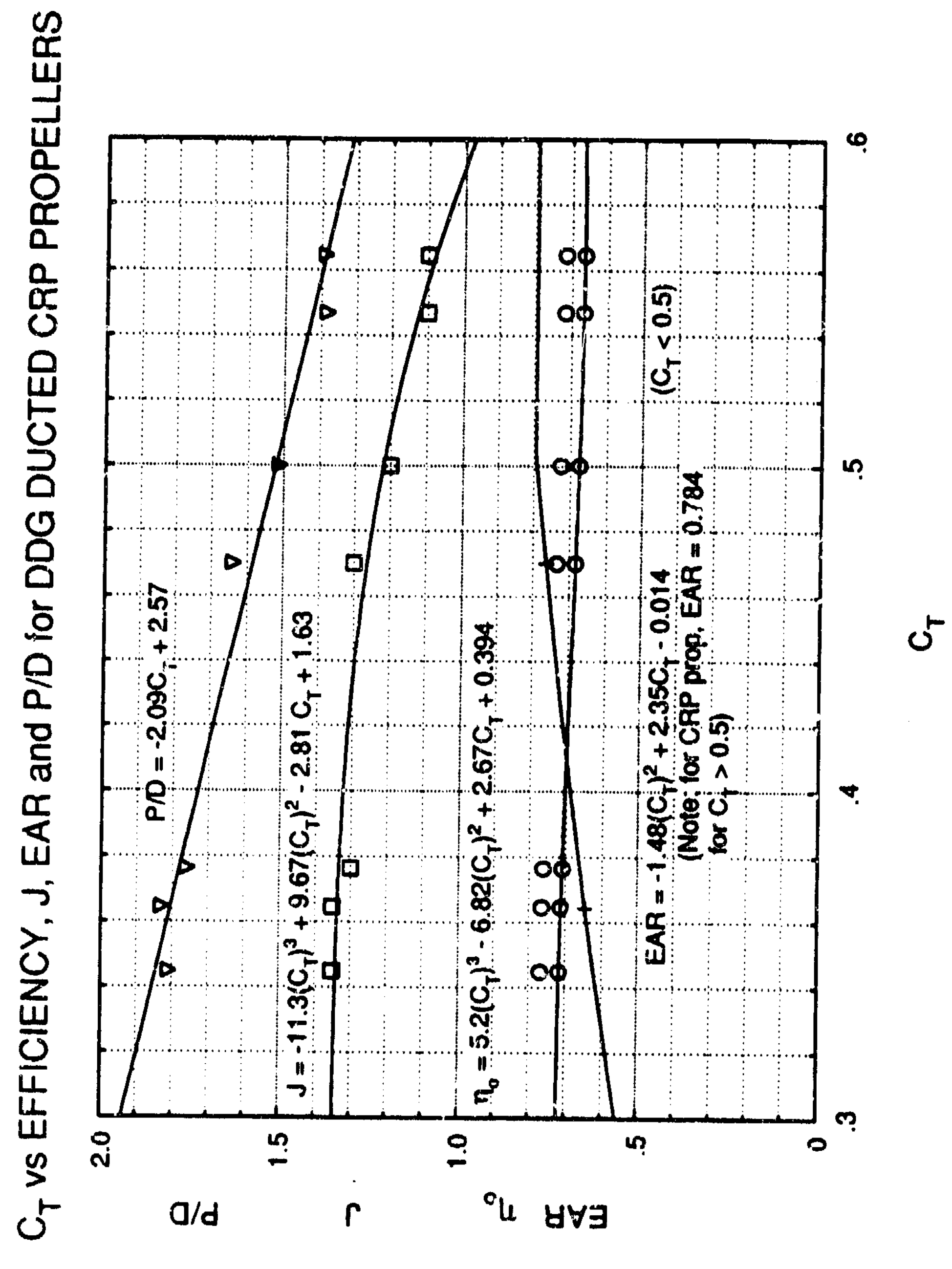

C_T vs EFFICIENCY, J, EAR and P/D for DDG PROPELLER with PRESWIRL STATOR
P/D = 1.058e^(-8.206C_T) + 1.105
J = -38.2(C_T)^3 + 54.1(C_T)^2 - 26.3 C_T + 5.60
η_o = -0.133C_T + 0.803
EAR = -4.51(C_T)^2 + 5.26 C_T - 0.633
P/D
J
η_o
EAR
C_T
2.0
1.5
1.0
.5
0
.3
.4
.5
.6

Figure A3.4



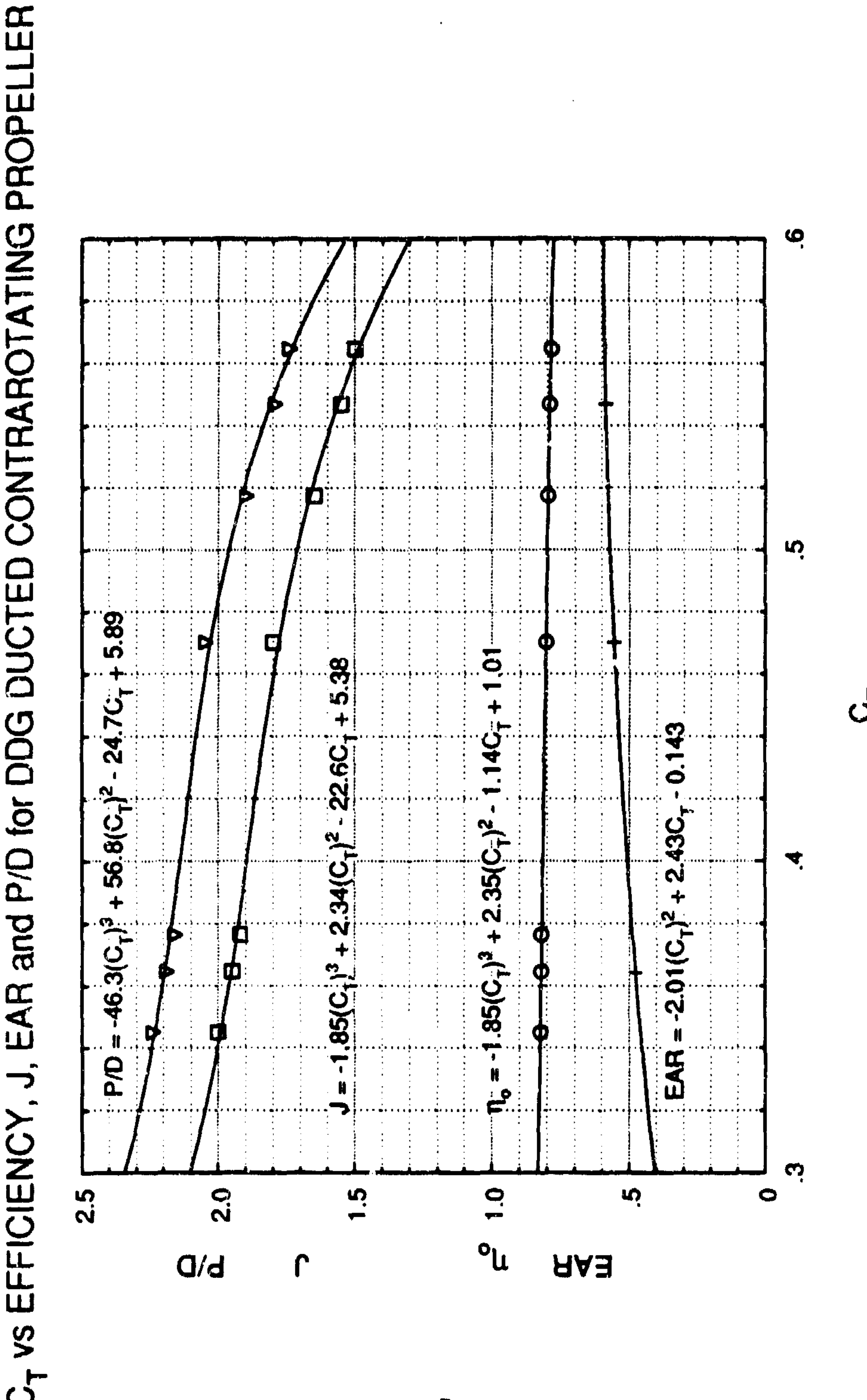
C_T vs EFFICIENCY, J and P/D for DDG DUCTED FIXED PITCH PROPELLER
$P/D = -2.09C_T + 2.57$
$J = -11.3(C_T)^3 + 9.67(C_T)^2 - 2.81\ C_T + 1.63$
$\eta_o = 5.20(C_T)^3 - 6.82(C_T)^2 + 2.67\ C_T + 0.446$
$EAR = -1.48(C_T)^2 + 2.35C_T - 0.014$
P/D
J
η_o
EAR
2.0
1.5
1.0
.5
0
.3
.4
.5
.6
C_T

Figure A3.5



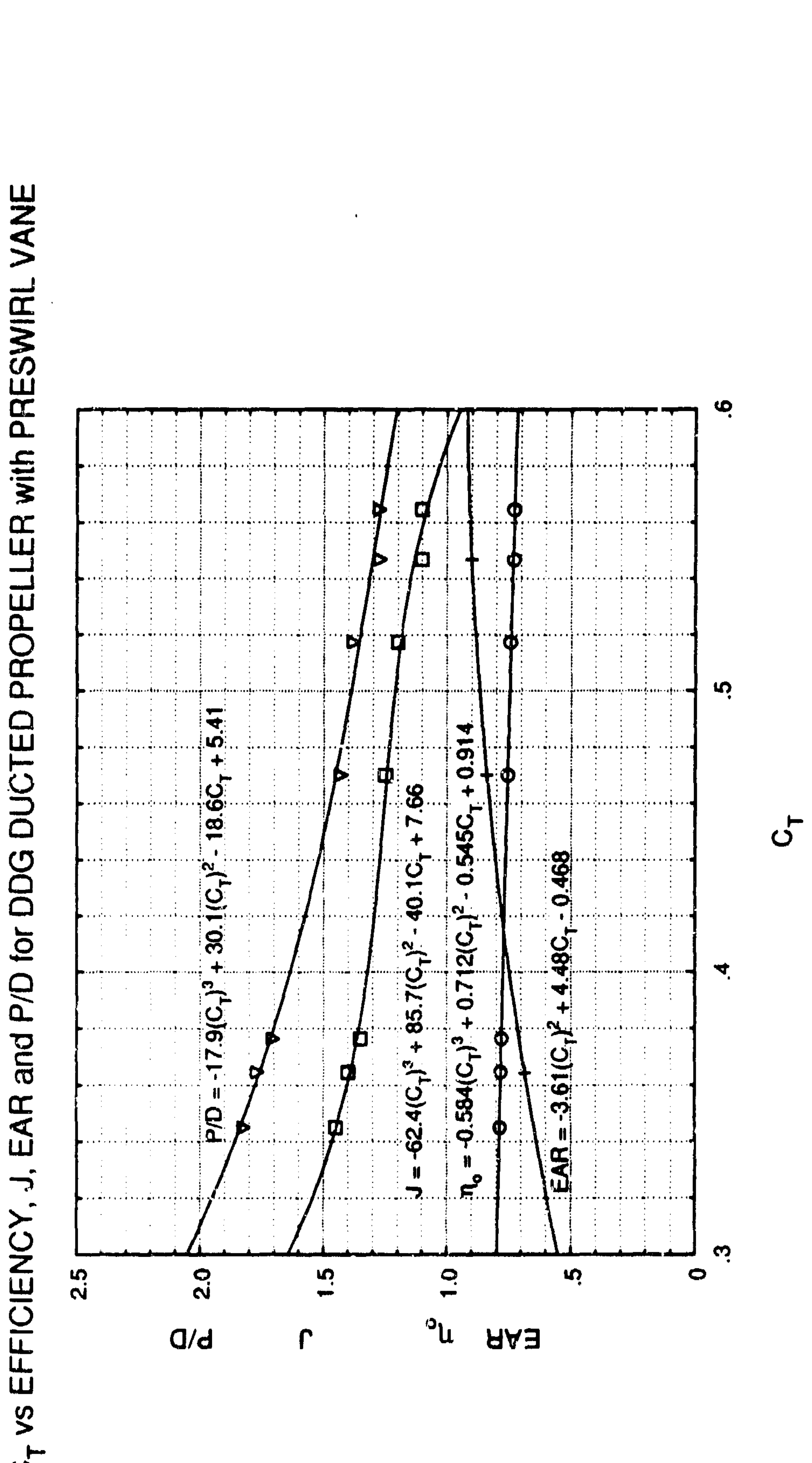
C_T vs EFFICIENCY, J, EAR and P/D for DDG DUCTED CRP PROPELLERS
P/D
J
EAR η_o
C_T
$P/D = -2.09C_T + 2.57$
$J = -11.3(C_T)^3 + 9.67(C_T)^2 - 2.81\,C_T + 1.63$
$\eta_o = 5.2(C_T)^3 - 6.82(C_T)^2 + 2.67C_T + 0.394$
$EAR = -1.48(C_T)^2 + 2.35C_T - 0.014$ $(C_T < 0.5)$
(Note: for CRP prop, EAR = 0.784 for $C_T > 0.5$)
2.0
1.5
1.0
.5
0
.3
.4
.5
.6

Figure A3.6



C_T vs EFFICIENCY, J, EAR and P/D for DDG DUCTED CONTRAROTATING PROPELLER
P/D = -46.3(C_T)^3 + 56.8(C_T)^2 - 24.7C_T + 5.89
J = -1.85(C_T)^3 + 2.34(C_T)^2 - 22.6C_T + 5.38
η_o = -1.85(C_T)^3 + 2.35(C_T)^2 - 1.14C_T + 1.01
EAR = -2.01(C_T)^2 + 2.43C_T - 0.143
P/D
J
η_o
EAR
2.5
2.0
1.5
1.0
.5
0
.3
.4
.5
.6
C_T

Figure A3.7



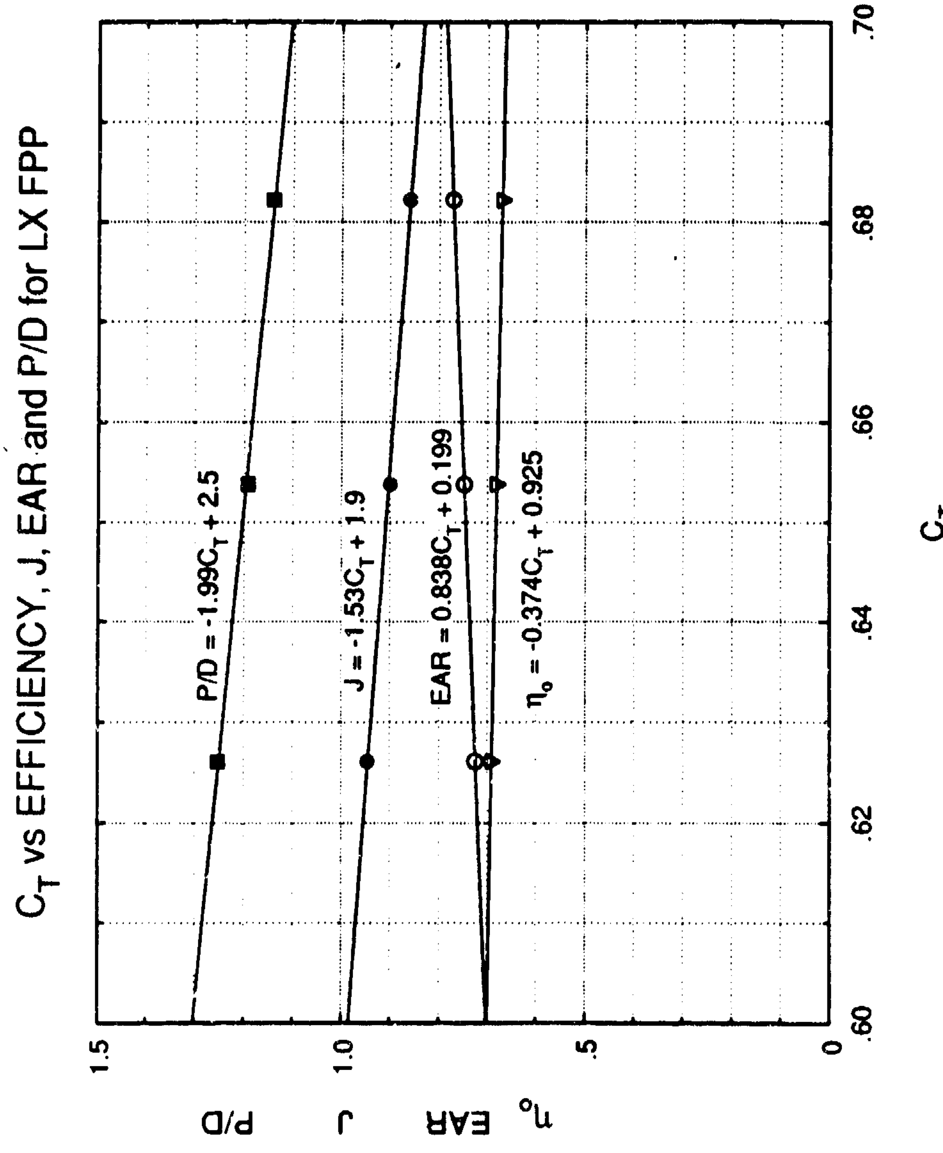
C_T vs EFFICIENCY, J, EAR and P/D for DDG DUCTED PROPELLER with PRESWIRL VANE
P/D = -17.9(C_T)^3 + 30.1(C_T)^2 - 18.6C_T + 5.41
J = -62.4(C_T)^3 + 85.7(C_T)^2 - 40.1C_T + 7.66
η_o = -0.584(C_T)^3 + 0.712(C_T)^2 - 0.545C_T + 0.914
EAR = -3.61(C_T)^2 + 4.48C_T - 0.468
P/D
J
η_o
EAR
2.5
2.0
1.5
1.0
.5
0
.3
.4
.5
.6
C_T

Figure A3.8

Appendix Four

Amphibious Ship Propeller Design Performance

Figures A4.1-A4.2 depict amphibious ship propeller open water efficiency versus thrust coefficient for the propeller types considered during this project. All data in these figures represent propellers which satisfied the cavitation standard developed for the amphibious ship design (<14.5% back cavitation when evaluated using Burrill criterion at 23.25 knot ship speed). The thrust coefficients in these figures represent thrust at 23.25 knots.



C_T vs EFFICIENCY, J, EAR and P/D for LX FPP
P/D = -1.99C_T + 2.5
J = -1.53C_T + 1.9
EAR = 0.838C_T + 0.199
η_o = -0.374C_T + 0.925
P/D
J
EAR
η_o
1.5
1.0
.5
0
.60
.62
.64
.66
.68
.70
C_T

Figure A4.1

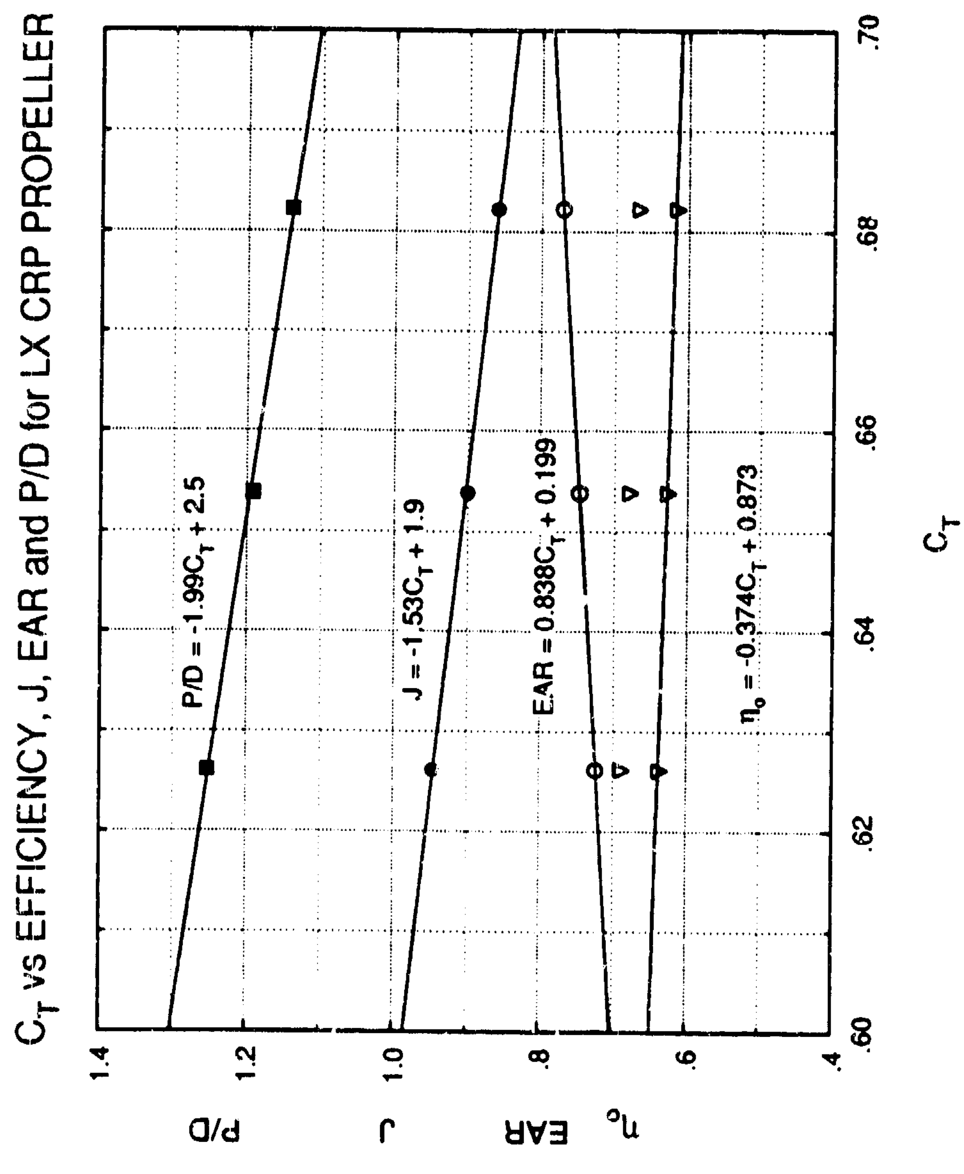

CT vs EFFICIENCY, J, EAR and P/D for LX CRP PROPELLER
P/D = -1.99CT + 2.5
J = -1.53CT + 1.9
EAR = 0.838CT + 0.199
ηo = -0.374CT + 0.873
P/D
J
EAR
ηo
1.4
1.2
1.0
.8
.6
.4
.60
.62
.64
.66
.68
.70
CT

Figure A4.2

Appendix Five

Submarine Propeller Design Performance

Figure A5.1 depicts submarine contrarotating propeller open water efficiency versus thrust coefficient. All data in this figure represent propellers which satisfied the cavitation standard developed for the submarine design (0% back cavitation when evaluated using Burrill criterion at 27 knot ship speed). The thrust coefficients in these figures represent thrust at 27 knots.

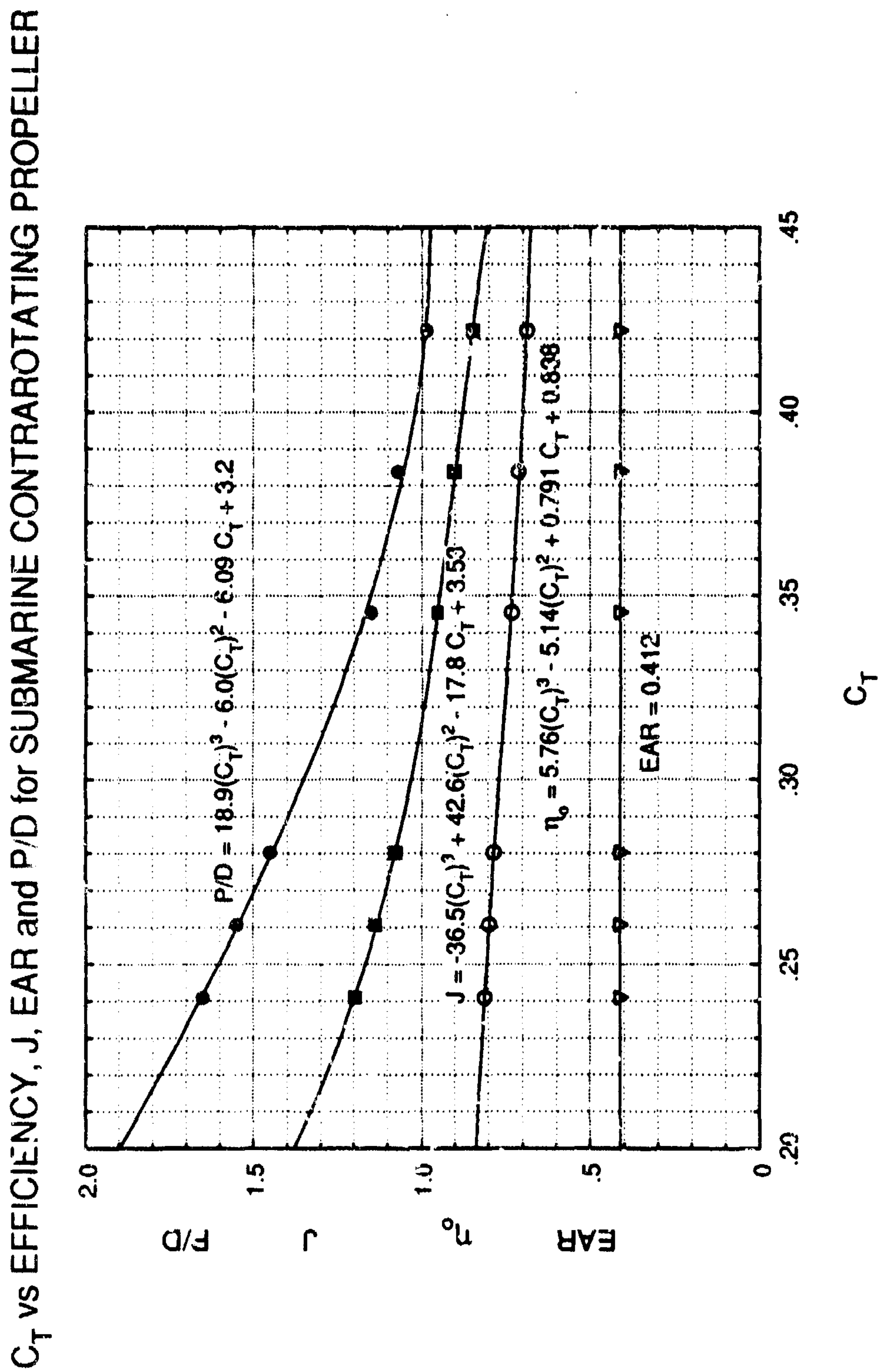

C_T vs EFFICIENCY, J, EAR and P/D for SUBMARINE CONTRAROTATING PROPELLER
P/D = 18.9(C_T)^3 - 6.0(C_T)^2 - 6.09 C_T + 3.2
J = -36.5(C_T)^3 + 42.6(C_T)^2 - 17.8 C_T + 3.53
η_o = 5.76(C_T)^3 - 5.14(C_T)^2 + 0.791 C_T + 0.838
EAR = 0.412
P/D
J
η_o
EAR
2.0
1.5
1.0
.5
0
.20
.25
.30
.35
.40
.45
C_T

Figure A5.1

Appendix Six

Destroyer Propeller Off-design Performance

Figures A6.1-A6.8 depict destroyer propeller open water efficiency versus ship speed for the propeller types considered during this project. All data in these figures represent propellers which satisfied the cavitation standard developed for the destroyer design (<20.7% back cavitation when evaluated using Burrill criterion at 29 knot ship speed). Curves are plotted for each propeller type for three separate propeller designs, each representing the optimum propeller design at the associated thrust coefficient. The thrust coefficients in these figures represent thrust at 29 knots for three destroyer configurations:

- CT = 0.364 corresponds with a 9060 ton destroyer propelled by three propellers,
- CT = 0.47 corresponds with an 8300 ton destroyer propelled by twin propellers, and
- CT = 0.547 corresponds with a 9060 ton destroyer propelled by twin propellers.

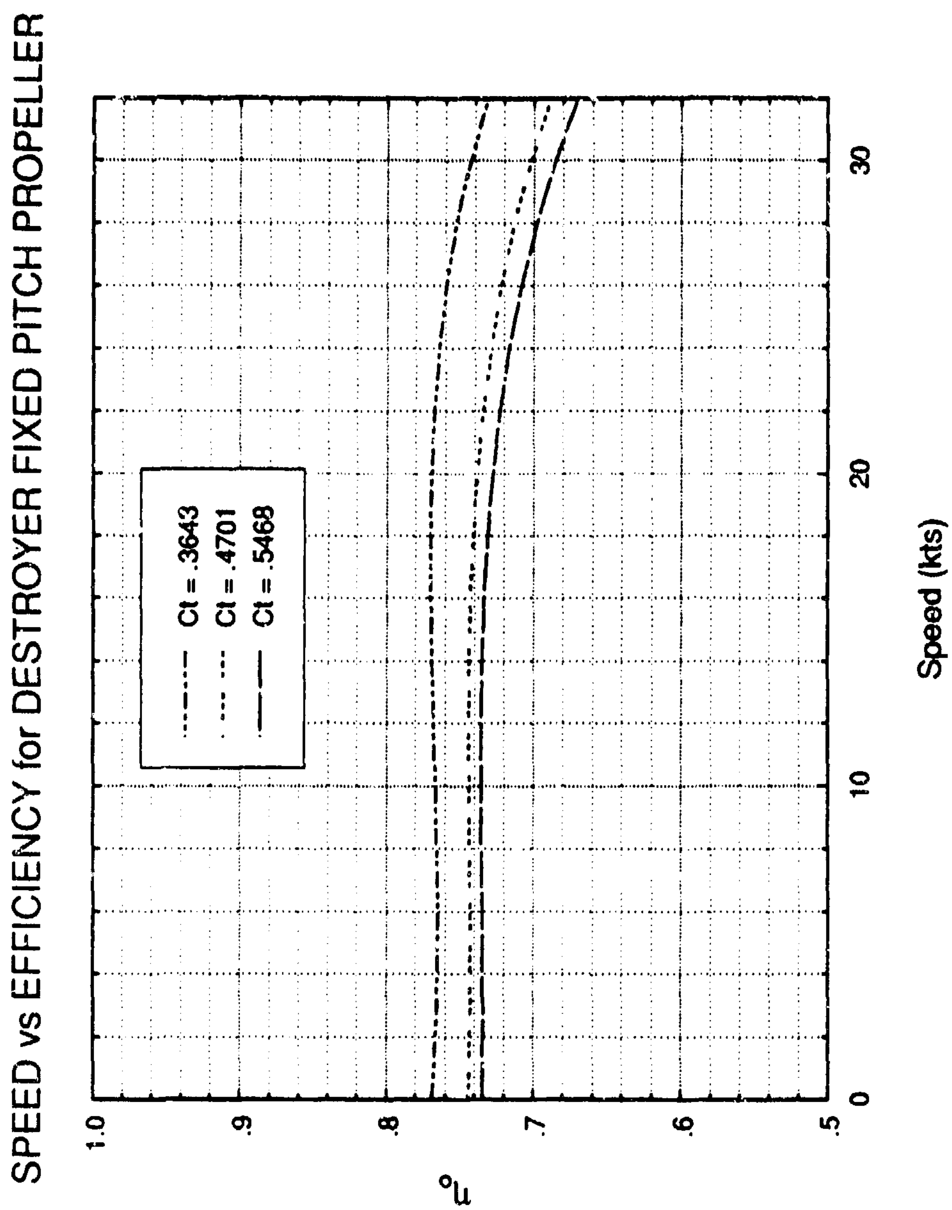

SPEED vs EFFICIENCY for DESTROYER FIXED PITCH PROPELLER
Ct = .3643
Ct = .4701
Ct = .5468
1.0
.9
.8
.7
.6
.5
0
10
20
30
Speed (kts)

Figure A6.1

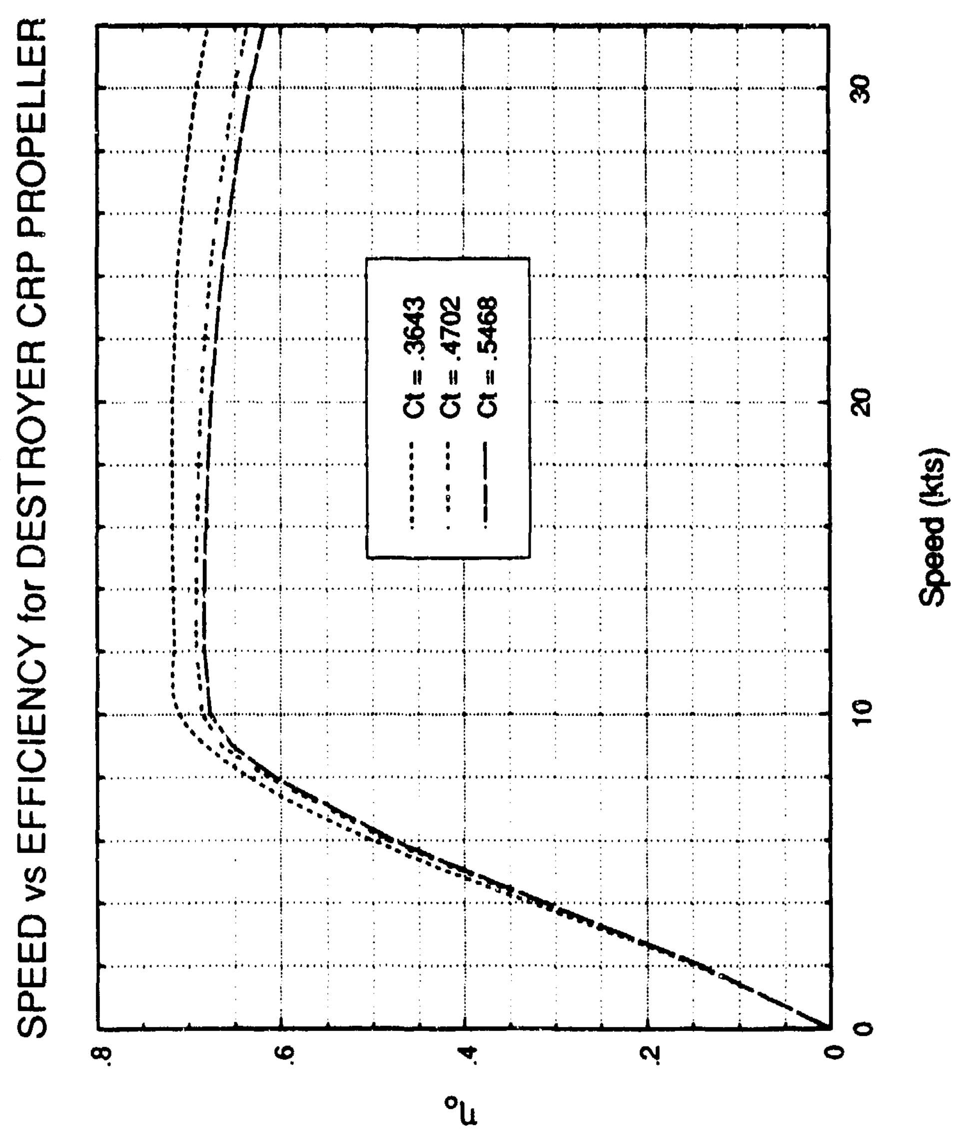

SPEED vs EFFICIENCY for DESTROYER CRP PROPELLER
Ct = .3643
Ct = .4702
Ct = .5468
Speed (kts)
η_o
0
.2
.4
.6
.8
0
10
20
30

Figure A6.2

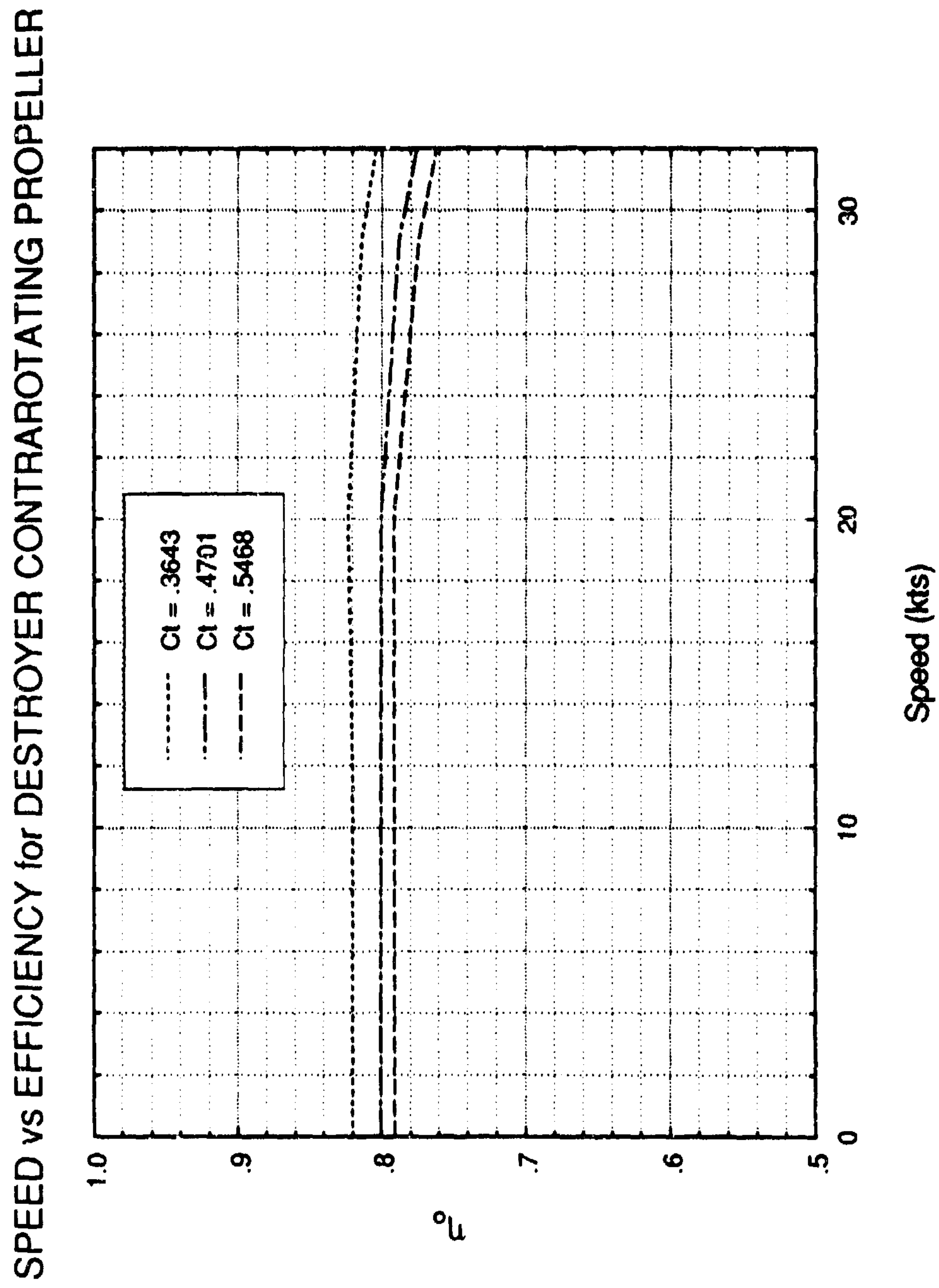

SPEED vs EFFICIENCY for DESTROYER CONTRAROTATING PROPELLER
Ct = .3643
Ct = .4701
Ct = .5468
1.0
.9
.8
.7
.6
.5
η₀
0
10
20
30
Speed (kts)

Figure A6.3

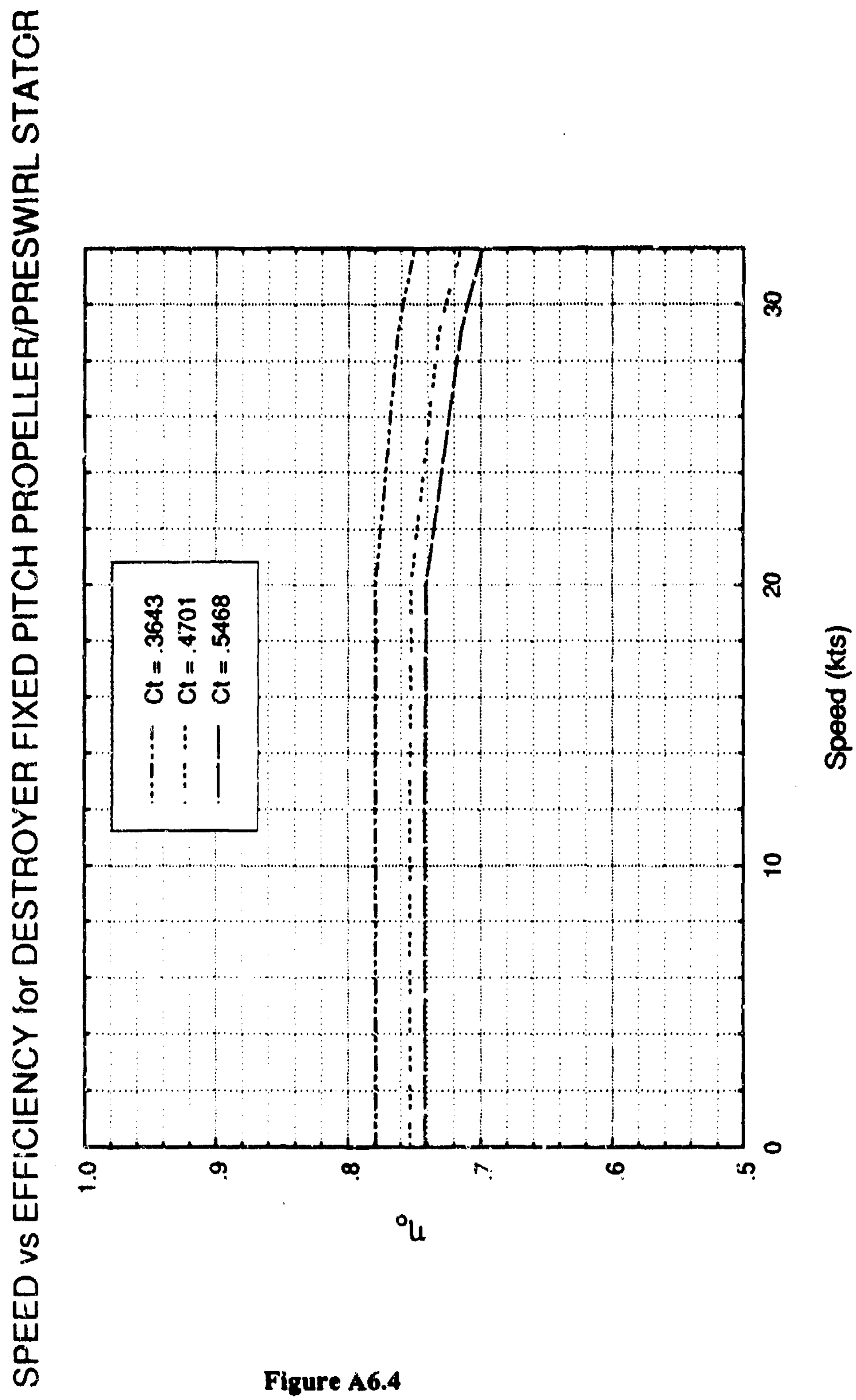

SPEED vs EFFICIENCY for DESTROYER FIXED PITCH PROPELLER/PRESWIRL STATCR
Ct = .3643
Ct = .4701
Ct = .5468
1.0
.9
.8
.7
.6
.5
η_o
0
10
20
30
Speed (kts)

Figure A6.4

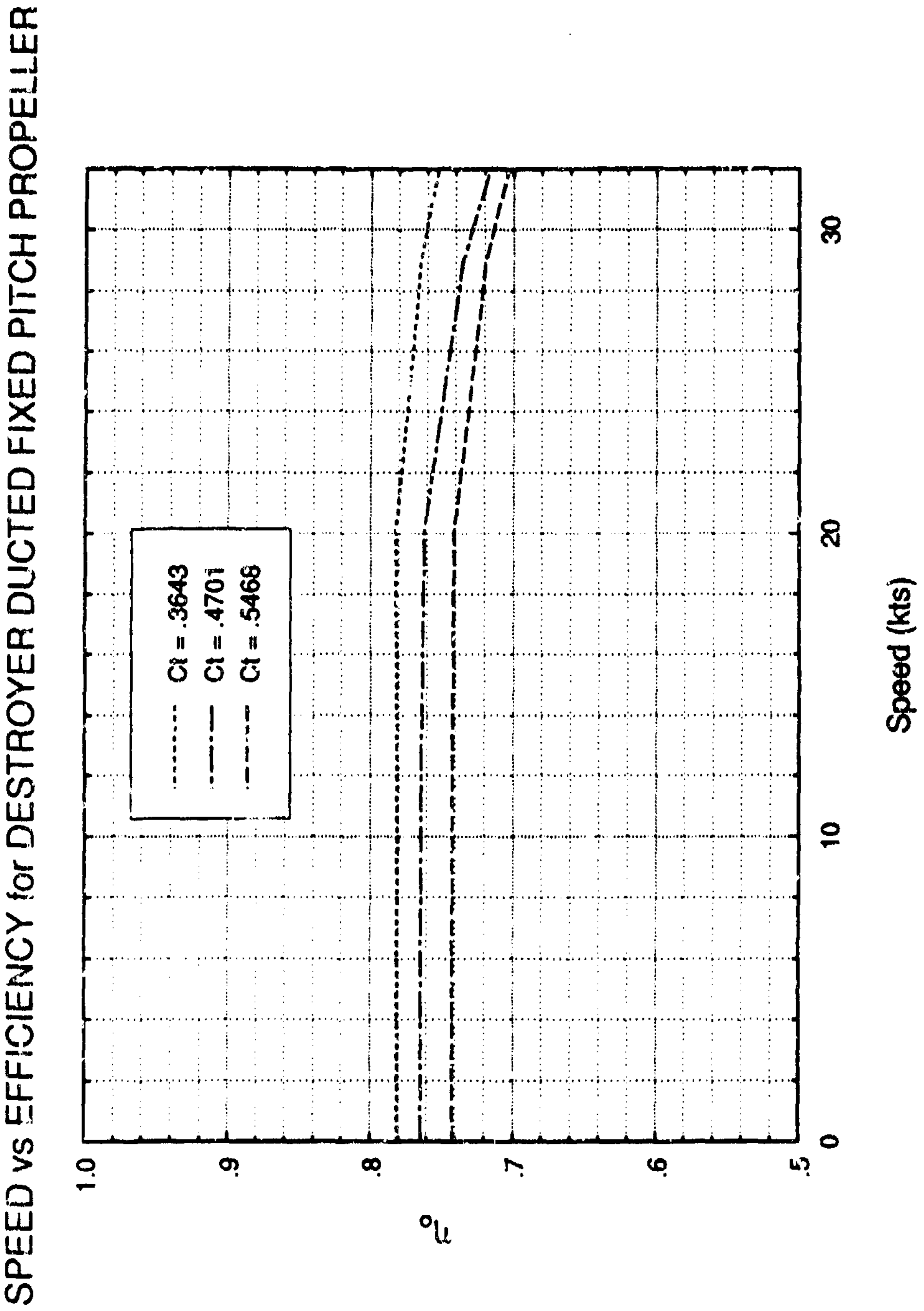

SPEED vs EFFICIENCY for DESTROYER DUCTED FIXED PITCH PROPELLER
Ct = .3643
Ct = .4701
Ct = .5466
Speed (kts)
η_o
1.0
.9
.8
.7
.6
.5
0
10
20
30

Figure A6.5

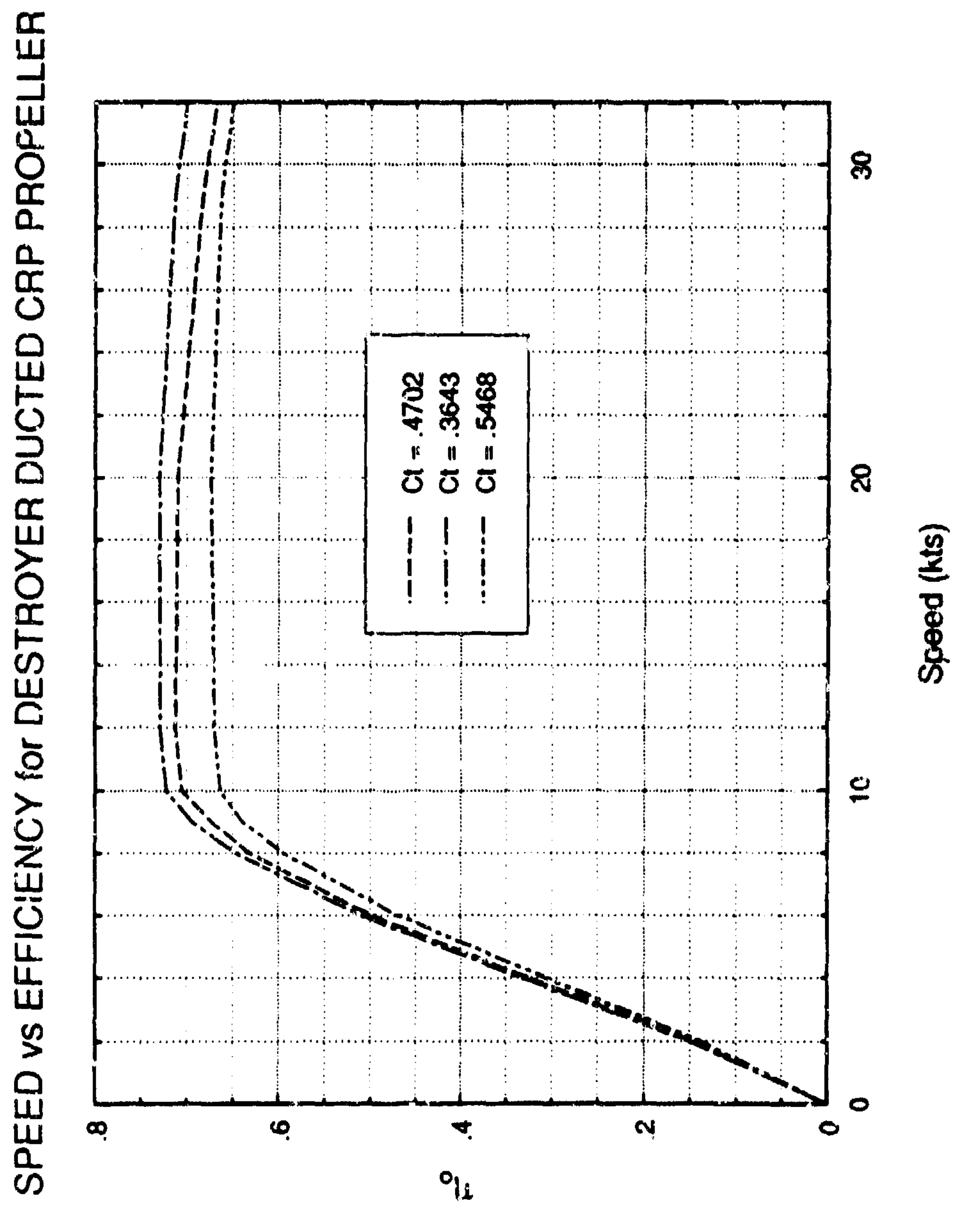

SPEED vs EFFICIENCY for DESTROYER DUCTED CRP PROPELLER
Ct = .4702
Ct = .3643
Ct = .5468
0
.2
.4
.6
.8
0
10
20
30
Speed (kts)

Figure A6.6

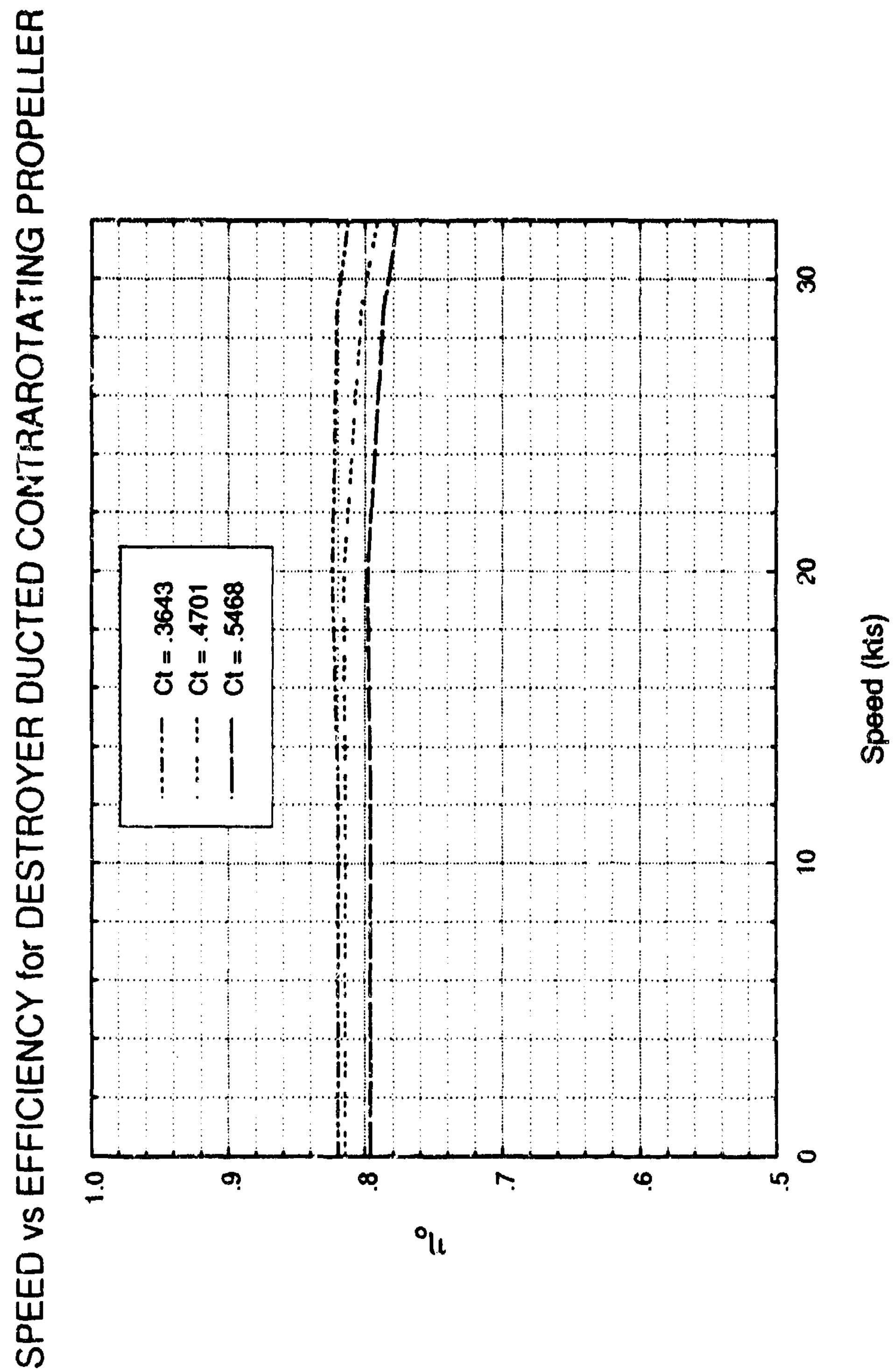

SPEED vs EFFICIENCY for DESTROYER DUCTED CONTRAROTATING PROPELLER
Ct = .3643
Ct = .4701
Ct = .5468
1.0
.9
.8
.7
.6
.5
η_o
0
10
20
30
Speed (kts)

Figure A6.7

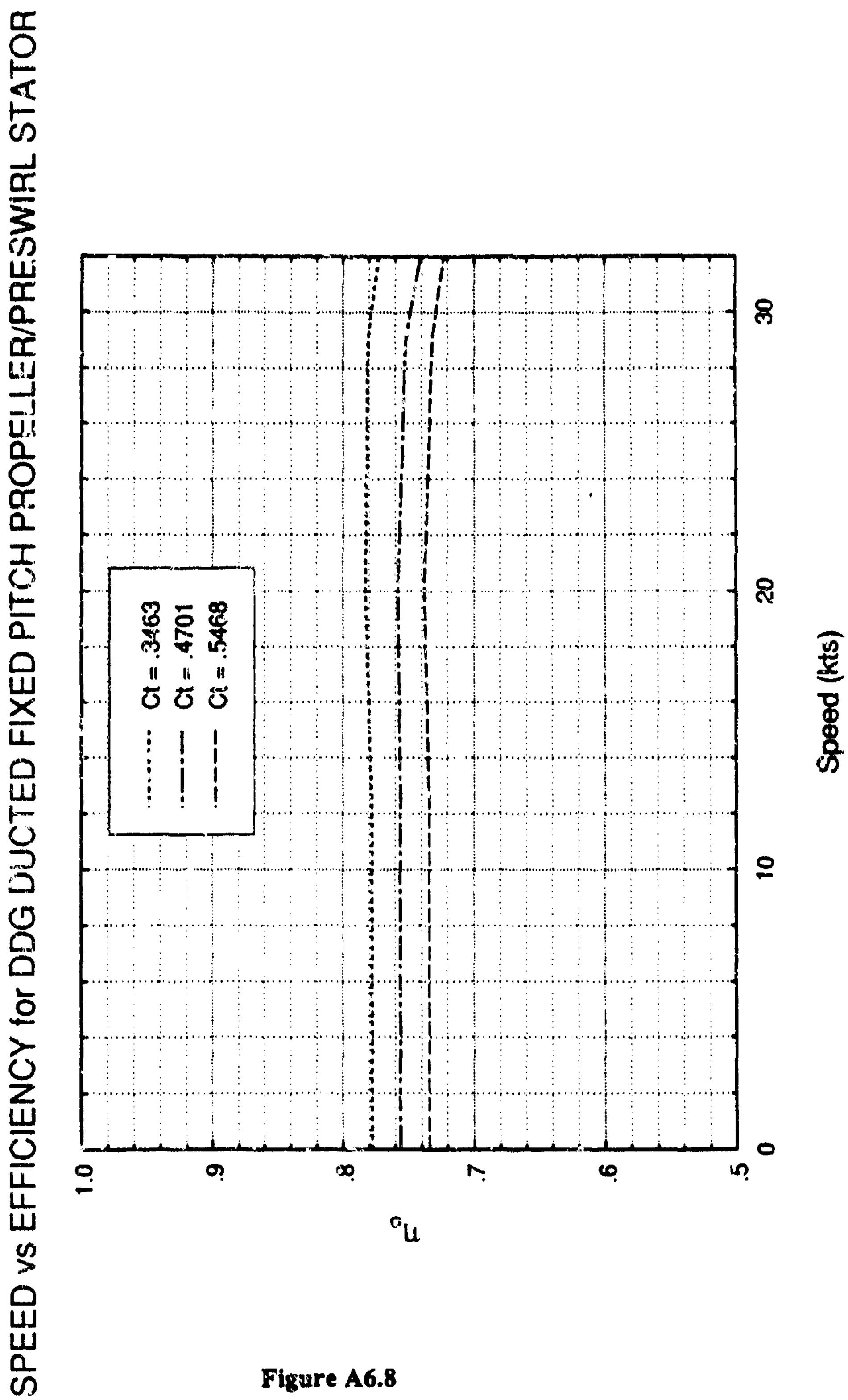

SPEED vs EFFICIENCY for DDG DUCTED FIXED PITCH PROPELLER/PRESWIRL STATOR
Ct = .3463
Ct = .4701
Ct = .5468
η_o
1.0
.9
.8
.7
.6
.5
0
10
20
30
Speed (kts)

Figure A6.8

Appendix Seven

Amphibious Ship Propeller Off-design Performance

Figures A7.1-A7.8 depict amphibious ship propeller open water efficiency versus ship speed for the propeller types considered during this project. All data in these figures represent propellers which satisfied the cavitation standard developed for the amphibious ship design (<14.5% back cavitation when evaluated using Burrill criterion at 23.25 knot ship speed). Curves are plotted for each propeller type for three separate propeller designs, each representing the optimum propeller design at the associated thrust coefficient. The thrust coefficients in these figures represent thrust at 23.25 knots for three amphibious ship configurations:

- C_T = 0.6261 corresponds with a 20,500 ton ship propelled by twin propellers,
- C_T = 0.6538 corresponds with an 22,700 ton ship propelled by twin propellers, and
- C_T = 0.6822 corresponds with a 25,000 ton ship propelled by twin propellers.

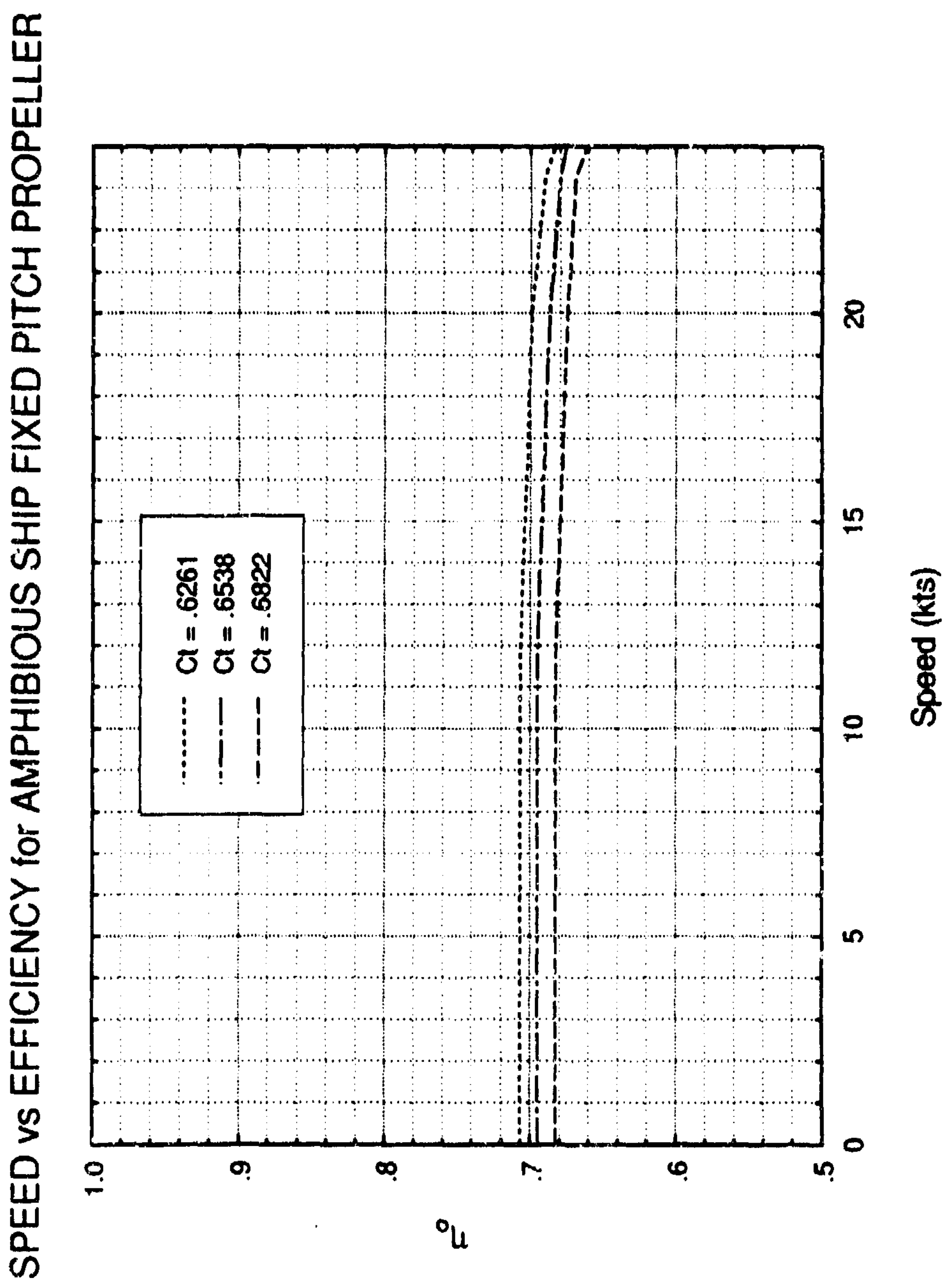

SPEED vs EFFICIENCY for AMPHIBIOUS SHIP FIXED PITCH PROPELLER
Ct = .6261
Ct = .6538
Ct = .6822
1.0
.9
.8
.7
.6
.5
ηo
0
5
10
15
20
Speed (kts)

Figure A7.1

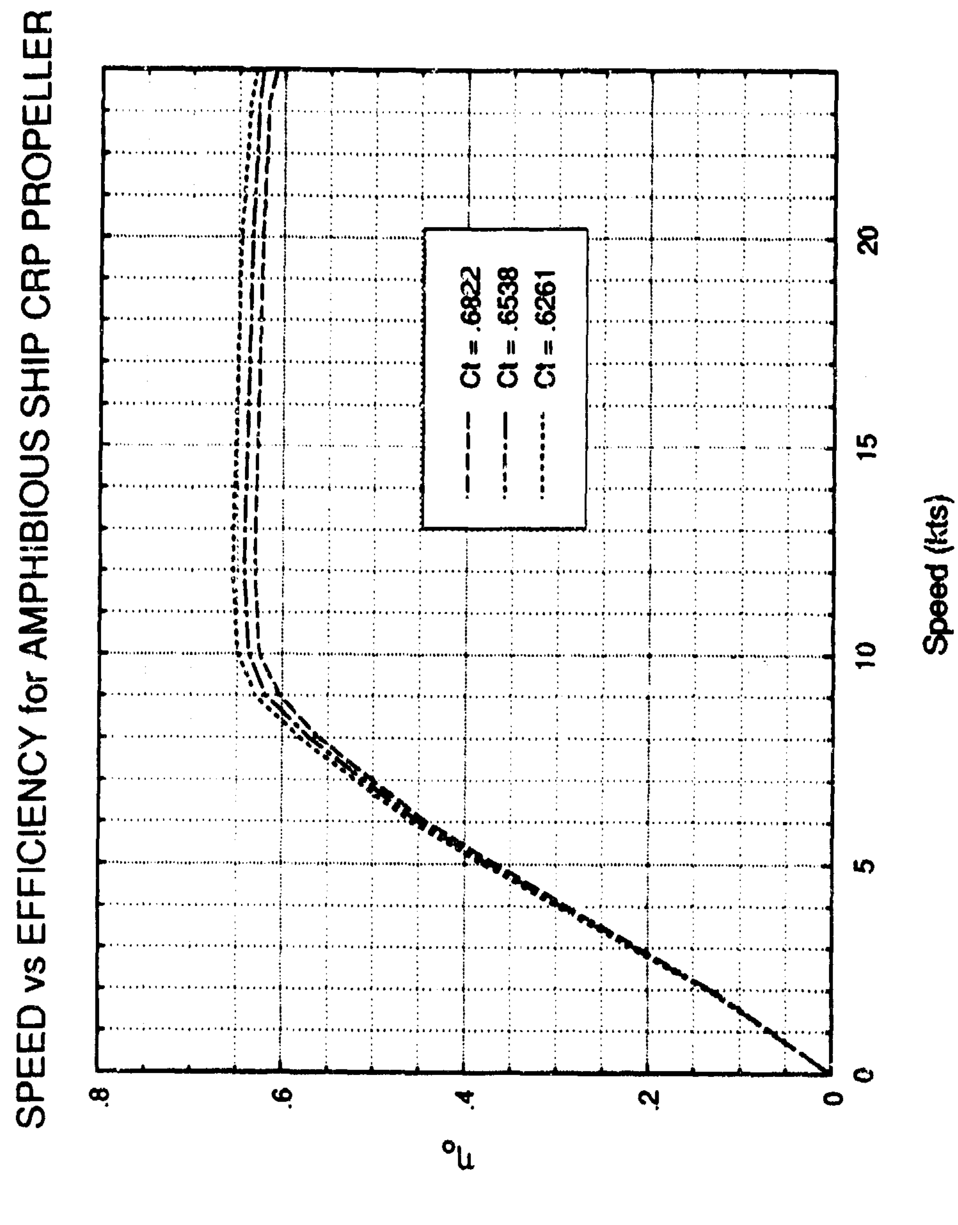

SPEED vs EFFICIENCY for AMPHIBIOUS SHIP CRP PROPELLER
Ct = .6822
Ct = .6538
Ct = .6261
0
.2
.4
.6
.8
0
5
10
15
20
Speed (kts)

Figure A7.2

Appendix Eight

Submarine Propeller Off-design Performance

Figure A8.1 depicts propeller open water efficiency versus ship speed for submarine contrarotating propellers. All data in this figure represent propellers which satisfied the cavitation standard developed for the submarine design (0% back cavitation when evaluated using Burrill criterion at 27 knot ship speed). Curves are plotted for each propeller type for three separate propeller designs, each representing the optimum propeller design at the associated thrust coefficient. The thrust coefficients in these figures represent thrust at 27 knots for three submarine designs:

- $C_T = 0.3454$ corresponds with a 6000 ton submarine propelled by a single propulsor,
- $C_T = 0.3837$ corresponds with a 7000 ton submarine propelled by a single propulsor, and
- $C_T = 0.4221$ corresponds with a 8000 ton submarine propelled by a single propulsor.

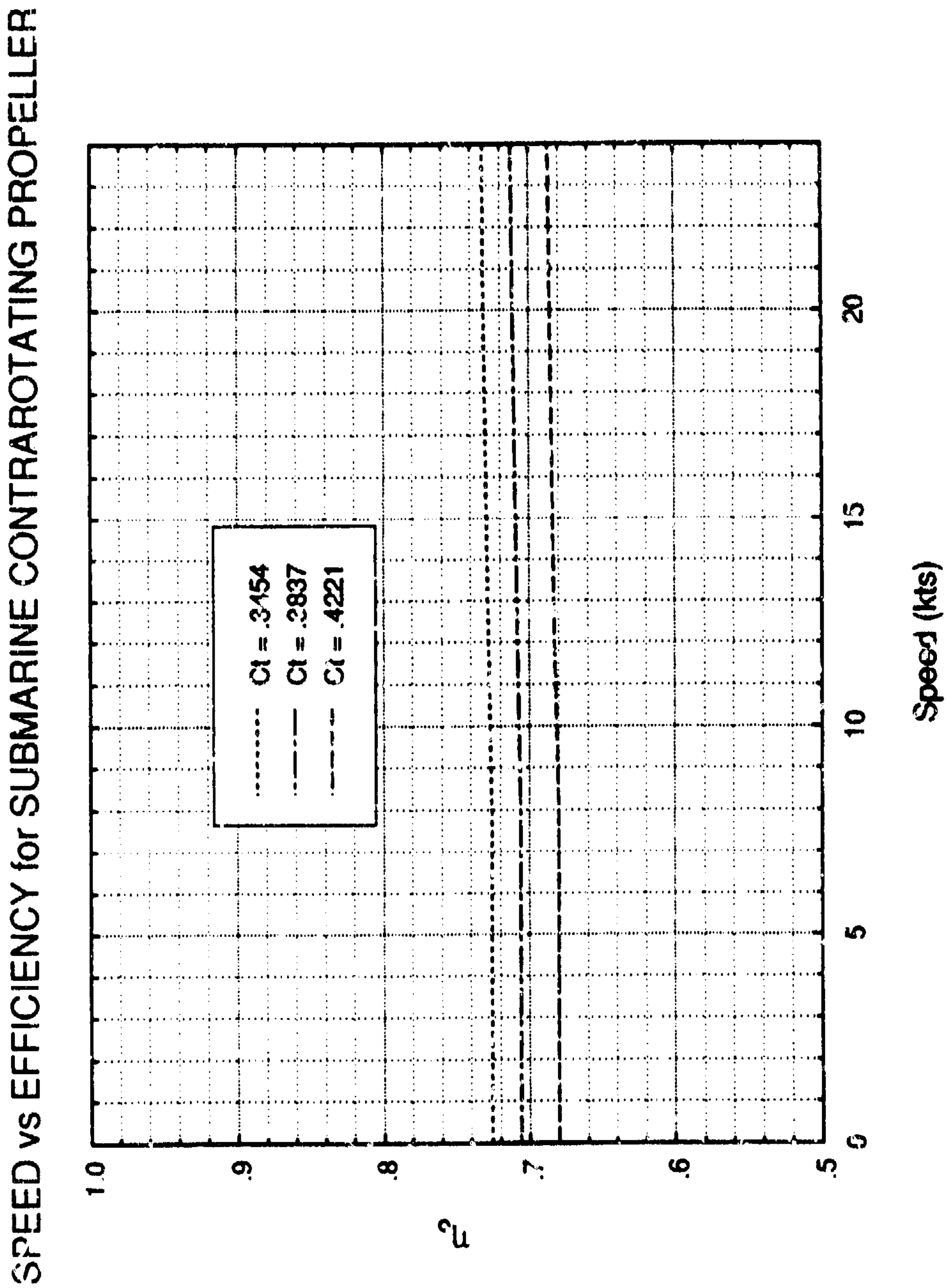
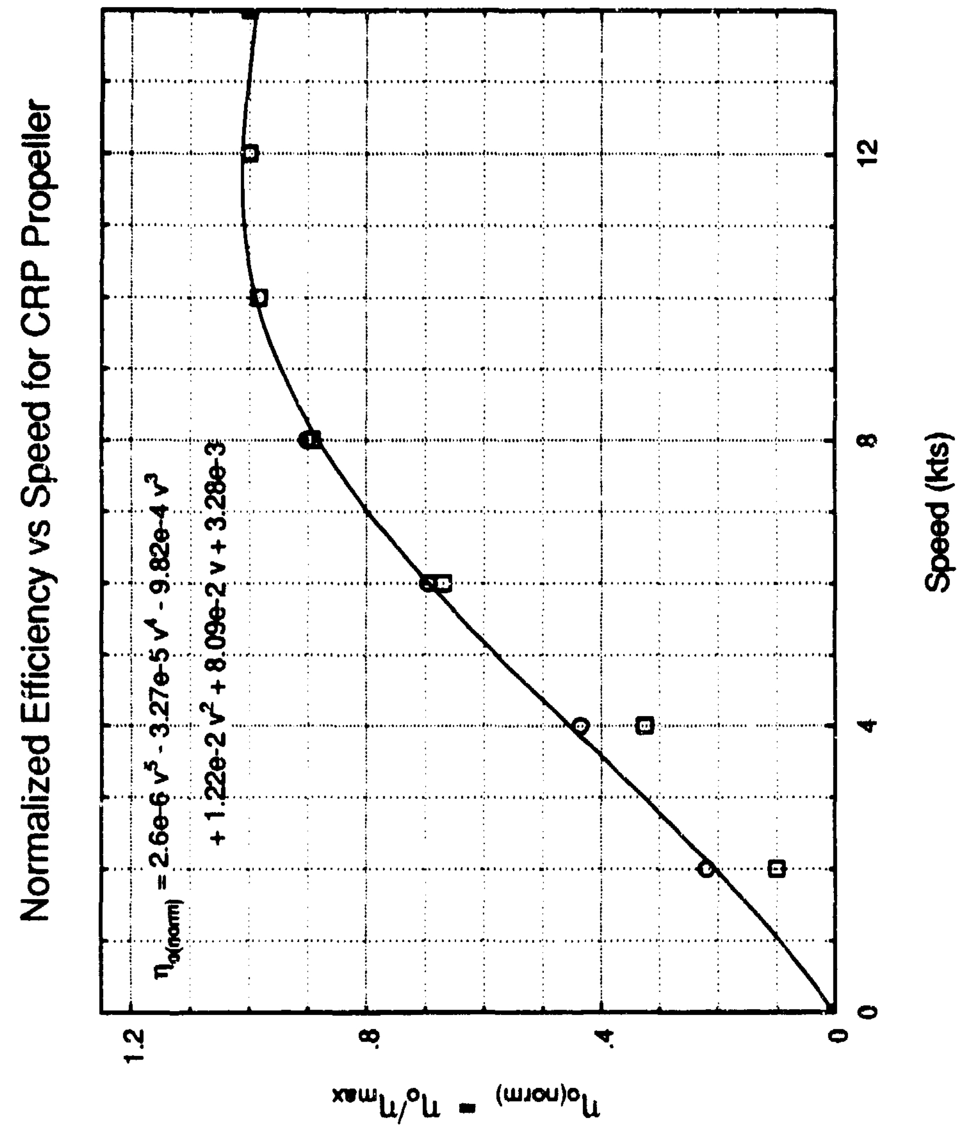

SPEED vs EFFICIENCY for SUBMARINE CONTRAROTATING PROPELLER
Ct = .3454
Ct = .3837
Ct = .4221
1.0
.9
.8
.7
.6
.5
0
5
10
15
20
Speed (kts)

Figure A8.1

Appendix Nine

Controllable Reversible Pitch Propeller Performance During Constant Speed / Varying Pitch Operation

Figure A9.1 shows the correlation developed to characterize the performance of CRP propellers during the constant rpm / varying pitch regime of operation (typically from 0 to 12 knots). The data points plotted were predicted using the Wageningen B-series propeller polynomial by matching ship speed vs thrust required with ship speed vs thrust developed by the propeller, while assuming the propeller rpm was constant and the pitch-to-diameter ratio varied. Data was gathered for different ship configurations, and it was noted that if the efficiencies were normalized by dividing by the peak efficiency, the same curve could be used to correlate normalized efficiency to speed for all CRP propellers analyzed. The correlation is included on Figure A9.1.



Normalized Efficiency vs Speed for CRP Propeller
$\eta_{o(norm)} = 2.6e\text{-}6\ v^5 - 3.27e\text{-}5\ v^4 - 9.82e\text{-}4\ v^3$
$+ 1.22e\text{-}2\ v^2 + 8.09e\text{-}2\ v + 3.28e\text{-}3$
1.2
.8
.4
0
$\eta_{o(norm)} = \eta_o/\eta_{max}$
0
4
8
12
Speed (kts)

Figure A9.1

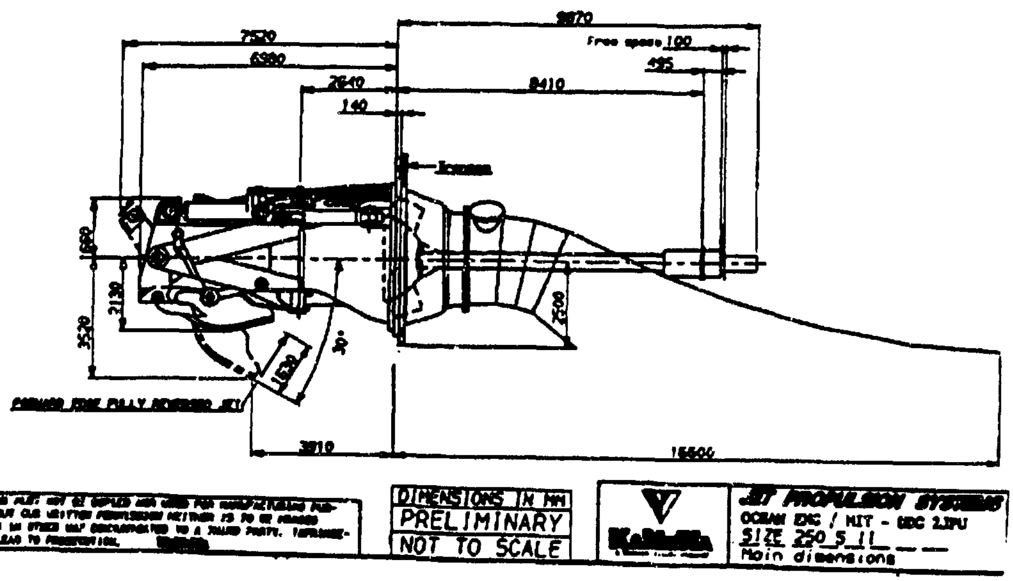
Appendix Ten

Waterjet Performance

Figure A10.1 depicts the propulsive coefficient vs speed relationship for waterjets to be used in a destroyer-sized ship design. The data are taken from information provided by the waterjet manufacturer *KaMeWa*. The following ship speed to propulsive coefficient correlation was developed by fitting a curve to this data:

$$(Q)PC = -.0145v_s^9 + .237v_s^8 - 1.64v_s^7 + 6.30v_s^6 - 14.6v_s^5 + 20.9v_s^4 - 17.8v_s^3 + 8.01v_s^2 - .884v_s - .000327 \ .$$

A schematic of the *KaMeWa* waterjet modelled by this correlation is provided below.



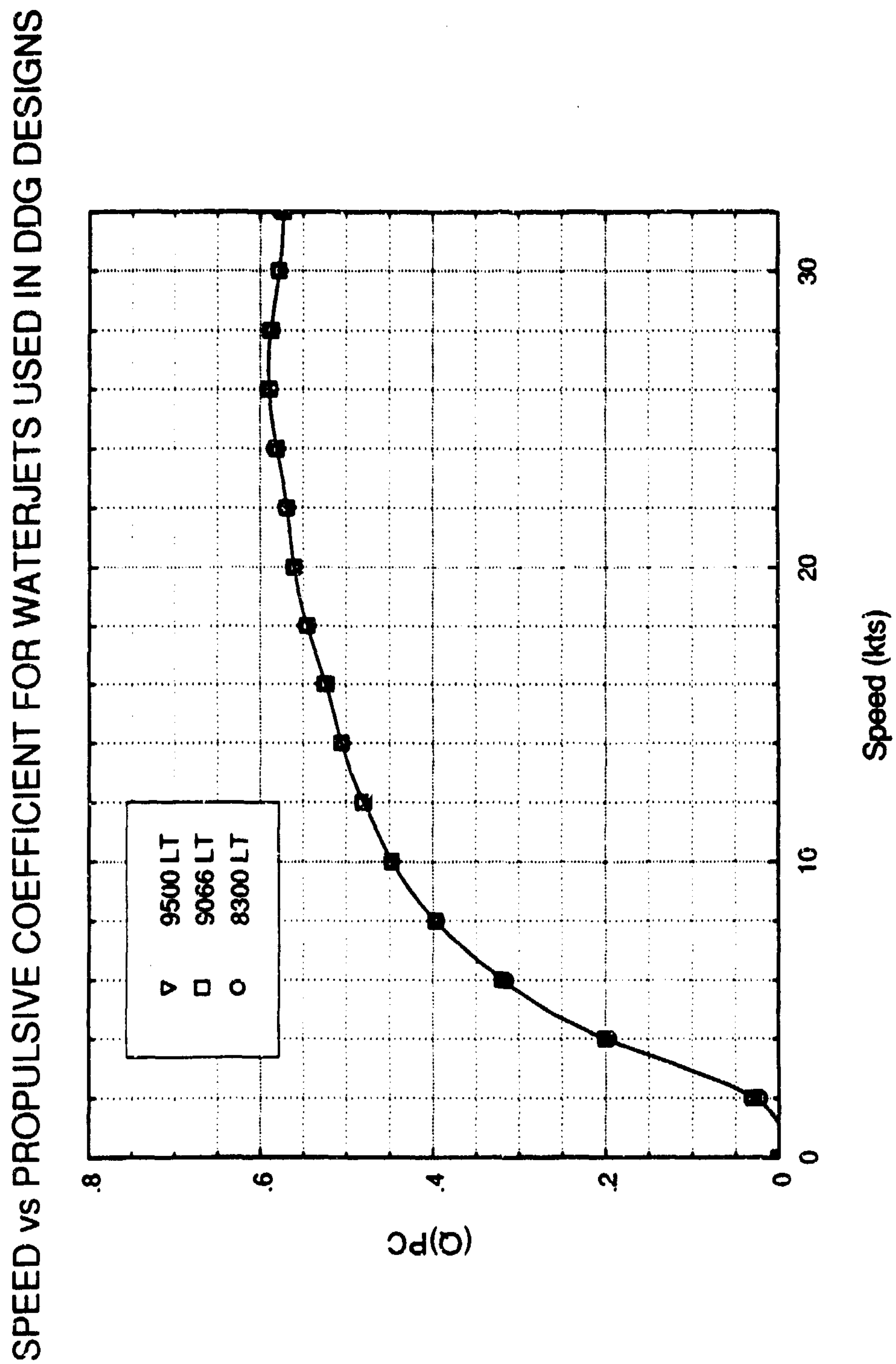

SPEED vs PROPULSIVE COEFFICIENT FOR WATERJETS USED IN DDG DESIGNS
(Q)PC
Speed (kts)
0
.2
.4
.6
.8
0
10
20
30
9500 LT
9066 LT
8300 LT

Figure A10.1

Appendix Eleven

Computer Routines for Selecting Optimum Propeller Geometry

Prop_Design for Destroyer Design

```
/* This module is designed to provide for determination of the propeller geometries for
several types of DDG propellers. It takes as input the number of propulsors, propulsor
type of interest, propeller diameter and resistance at the design speed. The correlations
included herein to establish the geometry of the propulsor of choice is based on data
collected for propellers which satisfy the same cavitation criteria as the existing DDG-51
propellers. The data was obtained for the propellers by running the Propeller Lifting
Line computer program. */


#include "propmain.h"

void prop_design(int n_propulsors, int propulsor_designation, double resistance_design,
                        double *PDR, double *EAR)
{
 double thrust_per_prop;
 double Ct;
 double thrust_ded = 0.945;      /* 1-t */
double Vs_design = 29. * 1.68781;
 double prop_area;
 double Dp;
 if(n_propulsors == 2)
   Dp = 17.;
 else              /* assume 3 propulsors */
   Dp = 15.2;
 prop_area = (PI * Dp * Dp) / 4.;
 thrust_per_prop = resistance_design/(thrust_ded * n_propulsors);
Ct = (2. * thrust_per_prop) / (RHO_SW * Vs_design * Vs_design * prop_area);
*PDR = pitch_diameter(Ct,propulsor_designation);
*EAR = area_ratio(Ct,propulsor_designation);
 return;
}
```

/* This function returns the pitch to diameter ratio as it correlates with thrust coefficient for a selected DDG prop. */

```
double pitch_diameter(double Ct, int type_props)
{
 if(type_props == 1)           /* FPP */
  return(-99.8 * pow(Ct,3.)+ 137. * pow(Ct,2.) - 62.6 * Ct + 11.1);
 if(type_props == 2)           /* CRP */
  return(-11.0 * pow(Ct,3.)+ 8.70 * pow(Ct,2.) - 2.18 * Ct + 1.85);
 if(type_props == 3)           /* contrarotating */
  return(-26.7 * pow(Ct,3.)+ 42.2 * pow(Ct,2.) - 23 0 * Ct + 5.99);
 if(type_props == 4)           /* pre-swirl stator */
  return(1.058 * exp(-8.206*Ct) + 1.105);
 if(type_props == 5)           /* ducted FPP */
  return(-2.09 * Ct + 2.57);
 if(type_props == 6)           /* ducted CRP */
  return(-2.09 * Ct + 2.57);
 if(type_props == 7)           /* ducted contrarotating */
  return(-63.1 * pow(Ct,3.)+ 69.7 * pow(Ct,2.) - 27.3 * Ct + 5.87);
 if(type_props == 8)           /* ducted pre-swirl stator */
  return(-23.0 * pow(Ct,3.)+ 35.1 * pow(Ct,2.) - 19.8 * Ct + 5.30);
 return(0);
}
```

/* This function returns the expanded area ratio as it correlates with thrust coefficient for a selected DDG prop. */

```
double area_ratio(double Ct, int type_props)
{
 if(type_props == 1)           /* FPP */
  return(-6.14 * pow(Ct,2.) + 6.82 * Ct - 1.05);
 if(type_props == 2 && Ct <= 0.47)          /* CRP */
  return(-6.14 * pow(Ct,2.) + 6.82 * Ct - 1.05);
 if(type_props == 2 && Ct > 0.47)          /* CRP */
  return(0.799);
 if(type_props == 3)           /* contrarotating */
  return(-2.65 * pow(Ct,2.) + 3.00 * Ct - 0.267);
 if(type_props == 4)           /* pre-swirl stator */
  return(-4.51 * pow(Ct,2.) + 5.26 * Ct - 0.633);
 if(type_props == 5)           /* ducted FPP */
  return(-1.48 * pow(Ct,2.) + 2.35 * Ct - 0.014);
```

```
 if(type_props == 6 && Ct <= 0.47)          /* ducted CRP */
  return(-1.48 * pow(Ct,2.) + 2.35 * Ct - 0.014);
 if(type_props == 6 && Ct > 0.47)          /* CRP */
  return(0.784);
 if(type_props == 7)          /* ducted contrarotating */
  return(-2.01 * pow(Ct,2.) + 2.43 * Ct - 0.143);
 if(type_props == 8)          /* ducted pre-swirl stator */
  return(-3.61 * pow(Ct,2.) + 4.48 * Ct - 0.468);
 return(0);
}
```

Prop_Design for Amphibious Ship Design

/* This module is designed to provide for determination of the propeller geometries for two types of LX propellers. It takes as input the number of propulsors, propulsor type of interest, propeller diameter and resistance at the design speed. The correlations included herein to establish the geometry of the propulsor of choice is based on data collected for propellers which satisfy the same cavitation criteria as the existing LX propellers. The data was obtained for the propellers by running the Propeller Lifting Line computer program. */

```
#include "prop_lx.h"

void prop_design(int n_propulsors, int propulsor_designation, double resistance_design,
double *EAR)
{
 double thrust_per_prop;
 double Ct;
 double thrust_ded = 0.905;     /* 1-t */
 double Vs_design = 23.25 * 1.68781;
 double prop_area;
 double Dp;
 Dp = 16.;
 prop_area = (PI * Dp * Dp) / 4.;
 thrust_per_prop = resistance_design/(thrust_ded * n_propulsors);
 Ct = (2. * thrust_per_prop) / (RHO_SW * Vs_design * Vs_design * prop_area);
 *EAR = area_ratio(Ct,propulsor_designation);
 return;
}
```

/* This function returns the expanded area ratio as it correlates with thrust coefficient for a selected DDG prop. */

```
double area_ratio(double Ct, int type_props)
{
 if(type_props == 1)          /* FPP */
   return(0.838*Ct + .199);
 if(type_props == 2)          /* CRP */
   return(0.838*Ct + .199);
 return(0);
}
```

Appendix Twelve

Determination of Propeller Diameter for Three Propeller Destroyer

During PLL data collection, the diameter of the propellers to be used in a twin screw destroyer design was assumed to be 17 feet, which matches the DDG-51 propeller diameter. This assumption was used to evaluate the cavitation performance of PLL-designed propellers using Burrill's criterion. An alternate design to be studied for this project involved a three propeller destroyer design. Since three 17 foot propellers would be difficult to accommodate in a ship having a 45-50 foot beam, it was desired to determine the propeller diameter for a three screw design which has the same cavitation performance as the 17 foot propellers in a two shaft design.

Burrill's cavitation criterion is based on the relationship between a thrust coefficient, τ_c, and the local cavitation number at a distance of 70 percent of the radius from the hub centerline. Of these, tc accounts for the propeller geometry as seen in the definition:

$\tau_c = T / (A_p * q_r)$ where T = thrust, lbf

A_p = propeller projected area, ft² and
q_r = dynamic pressure at 0.7*radius, psi.

For the cavitation performance of the two propellers having different diameters to be the same, $\tau_{c(2\ prop)} = \tau_{c(3\ prop)}$. Since the thrust required to be developed by a propeller in the 3 screw configuration is two thirds of the thrust needed to be developed by a propeller in the twin screw configuration, applying the definition of tc yields $$2\ A_{P(2prop)}\ q_{r(2prop)} = 3\ A_{P(3\ prop)}\ q_{r(3\ prop)} \quad . \qquad (1)$$

The propeller projected area, AP, is defined:

$$A_p = EAR\ (\pi R^2)\ (1.067 - .229\ PDR)$$

where EAR = expanded area ratio,
R = propeller radius, and
PDR = pitch-to-diameter ratio.

The local dynamic pressure is defined:

$q_r = \frac{1}{2}\rho V_r^2$ where $V_r^2 = V_a^2 + (.7\pi nD)^2$
and Va = ship advance speed,
n = propeller revolutions/second,
D = propeller diameter.

Since the propeller design correlations will choose the same EAR and PDR, and the ship advance speed is the same in both cases, equation (1) simplifies to:

$$2\ D_{(2prop)}^2 (V_a^2 + (.7\pi nD_{(2prop)})^2) = 3\ D_{(3prop)}^2 (V_a^2 + (.7\pi nD_{(3prop)})^2) \quad . \qquad (2)$$

For the destroyer, the cavitation design speed was 29 knots and the wake fraction, w, was 0.974, so that Va = ship speed (ft/sec) * (1-w) = 47.674 ft/sec . The propeller speed, n, at 29 knots is n = 150 rpm/60 = 2.5 revs/second. Substituting these values into equation (2) and assuming a twin screw propeller diameter, $D_{(2prop)}$, of 17 feet yields $D_{(3prop)}$ = 15.2 feet, which can be fit into a ship with a 45-50 foot beam.

Appendix Thirteen

Computer Routines for Predicting Off-design Propulsor Performance

Prop_Performance for Destroyer Design

/* This module is designed to provide performance estimate for several types of DDG propulsors. It takes as input the propulsor type of interest, propeller geometry information generated by the function prop_design and speed for which performance is required. It returns the QPC and RPM of the selected propulsor at that speed. Functions are included which invoke correlations for propeller performance based on data collected from the Propeller Lifting Line computer program. */

```
#include "propmain.h"

void prop_performance(int type_props, int num_cruise_prop, int n_props, double speed,
                double idle_speed, double EAR, double PDR, double *QPC,
                double *rpm)
{
 double thrust_ded = 0.945;      /* 1-t */
 double wake_frac = 0.974;       /* 1-w */
 double Va; double Dp;
 double jet_QPC,jet_rpm;
 if(type_props == 9)
 {
  jet_performance(speed, &jet_QPC, &jet_rpm);
  *QPC = jet_QPC;
  *rpm = jet_rpm;
  return;
 }
 if(n_props == 2)
  Dp = 17;
 else
  Dp = 15.2;
 Va = speed * 1.68781 * wake_frac;
 if(num_cruise_prop == 1)
 {
```

```
   speed = 1.6 * speed;
   Va = 1.6 * Va;
   *QPC = (efficiency(speed, idle_speed, EAR, PDR, type_props) * thrust_ded) /
             wake_frac;
   if(type_props == 2 && speed < idle_speed || type_props == 6 && speed <
             idle_speed)
   {
    speed = idle_speed;
    Va = speed * 1.68781 * wake_frac;
    *rpm = (Va * 60.)/(J(speed, EAR, PDR, type_props) * Dp);
   }
   else
    *rpm = (Va * 60.)/(J(speed, EAR, PDR, type_props) * Dp);
  }
 else
  {
   *QPC = (efficiency(speed, idle_speed, EAR, PDR, type_props) * thrust_ded) /
             wake_frac;
   if(type_props == 2 && speed < idle_speed || type_props == 6 && speed <
             idle_speed)
   {
    speed = idle_speed;
    Va = speed * 1.68781 * wake_frac;
    *rpm = (Va * 60.)/(J(speed, EAR, PDR, type_props) * Dp);
   }
   else
    *rpm = (Va * 60.)/(J(speed, EAR, PDR, type_props) * Dp);
  }
 return;
}


/* This function returns the open water efficiency of a selected DDG prop. */

double efficiency(double speed, double idle_speed, double EAR, double PDR,
                  int type_props)
{
 double eta;
 if(type_props == 1)                /* FPP */
 {
  eta = fpp_eta(speed, EAR);
        return(eta);
 }
```

```
if(type_props == 2 && EAR < 0.799)        /* CRP */
{
 if(speed < idle_speed)
  eta = crp_eta_low_speed(speed, idle_speed, PDR, EAR);
 else
  eta = fpp_eta(speed, EAR) - 0.052;
 return(eta);
}
if(type_props == 2 && EAR >= 0.799)       /* CRP */
{
 if(speed < idle_speed)
  eta = crp_eta_low_speed(speed, idle_speed, PDR, 0.799);
 else
  eta = crp_eta(speed, PDR);
 return(eta);
}
if(type_props == 3)           /* contrarotating */
{
 eta = contra_eta(speed, EAR);
 return(eta);
}
if(type_props == 4)           /* pre-swirl stator */
{
 eta = preswirl_eta(speed, EAR);
 return(eta);
}
if(type_props == 5)           /* ducted FPP */
{
 eta = ducted_fpp_eta(speed, EAR);
 return(eta);
}
if(type_props == 6 && EAR < 0.784)  /* ducted CRP */
{
 if(speed < idle_speed)
  eta = ducted_crp_eta_low_speed(speed, idle_speed, PDR, EAR);
 else
  eta = ducted_fpp_eta(speed, EAR) - 0.052;
 return(eta);
}
if(type_props == 6 && EAR >= 0.784)  /* ducted CRP */
{
 if(speed < idle_speed)
  eta = ducted_crp_eta_low_speed(speed, idle_speed, PDR, 0.784);
```

```
  else
    eta = ducted_crp_eta(speed, PDR);
  return(eta);
 }
 if(type_props == 7)          /* ducted contrarotating */
 {
  eta = ducted_contra_eta(speed, EAR);
  return(eta);
 }
 if(type_props == 8)          /* ducted pre-swirl stator */
 {
  eta = ducted_preswirl_eta(speed, EAR);
  return(eta);
 }
 return(0);
}


/* This function returns the advance coefficient at a particular speed for the DDG. */

double J(double speed, double EAR. double PDR, int type_props)
{
 double J;
 if(type_props == 1)             /* FPP */
 {
  J = fpp_J(speed, EAR);
  return(J);
 }
 if(type_props == 2 && EAR < 0.799)       /* CRP */
 {
  J = fpp_J(speed, EAR);
  return(J);
 }
 if(type_props == 2 && EAR >= 0.799)       /* CRP */
 {
  J = crp_J(speed, PDR);
  return(J);
 }
 if(type_props == 3)          /* contrarotating */
 {
  J = contra_J(speed, EAR);
  return(J);
 }
```

```
 if(type_props == 4)           /* pre-swirl stator */
 {
  J = preswirl_J(speed, EAR);
  return(J);
 }
 if(type_props == 5)           /* ducted FPP */
 {
  J = ducted_fpp_J(speed, EAR);
  return(J);
 }
 if(type_props == 6 && EAR < 0.784)  /* ducted CRP */
 {
  J = ducted_fpp_J(speed, EAR);
  return(J);
 }
 if(type_props == 6 && EAR >= 0.784) /* ducted CRP */
 {
  J = ducted_crp_J(speed, PDR);
  return(J);
 }
 if(type_props == 7)           /* ducted contrarotating */
 {
  J = ducted_contra_J(speed, EAR);
  return(J);
 }
 if(type_props == 8)           /* ducted pre-swirl stator */
 {
  J = ducted_preswirl_J(speed, EAR);
  return(J);
 }
 return(0);
}


double fpp_eta(double speed, double ear)
{
 double a0,a1,a2,a3,x,eta;
 a0 = -0.291*ear*ear + 0.273*ear + 0.711;
 a1 = 0.0257*ear*ear - 0.0345*ear + 0.0105;
 a2 = -0.00205*ear*ear + 0.00285*ear - 0.000866;
 a3 = 0.000041*ear*ear - 0.0000651*ear + 0.0000214;
 if (speed < 12.)
  eta = a3*pow(12.,3.) + a2*pow(12.,2.) + a1*12. + a0;
```

```
 else
  eta = a3*pow(speed,3.) + a2*pow(speed,2.) + a1*speed + a0;
 return(eta);
}


double crp_eta(double speed, double PDR)
{
 double a0,a1,a2,a3,x,eta;
 x = speed;
 a0 = 0.353*PDR + 0.143;
 a1 = -0.044*PDR + 0.0672;
 a2 = 0.00206*PDR - 0.00306;
 a3 = -0.0000299*PDR + 0.0000416;
 eta = a3*pow(x,3.) + a2*pow(x,2.) + a1*x + a0;
 return(eta);
}


double crp_eta_low_speed(double speed, double idle_speed, double PDR, double ear)
{
 double a0,a1,a2,a3,x,eta,b0,b1,b2,b3,b4,b5;
 x = speed;
 b0 = 0.00328;
 b1 = 0.0809;
 b2 = 0.0122;
 b3 = -0.000982;
 b4 = -0.0000327;
 b5 = 0.0000026;
 if (ear < .799)
 {
  a0 = -0.291*ear*ear + 0.273*ear + 0.659;
  a1 = 0.0257*ear*ear - 0.0345*ear + 0.0105;
  a2 = -0.00205*ear*ear + 0.00285*ear - 0.000866;
  a3 = 0.000041*ear*ear - 0.0000651*ear + 0.0000214;
  eta = (a3*pow(idle_speed,3.) + a2*pow(idle_speed,2.) + a1*idle_speed + a0) *
       (b5*pow(x,5.) + b4*pow(x,4.) + b3*pow(x,3.) + b2*pow(x,2.) + b1*x + b0);
 }
 else
 {
  a0 = 0.353*PDR + 0.143;
  a1 = -0.044*PDR + 0.0672;
  a2 = 0.00206*PDR - 0.00306;
```

```
  a3 = -0.0000299*PDR + 0.0000416;
  eta = (a3*pow(idle_speed,3.) + a2*pow(idle_speed,2.) + a1*idle_speed + a0) *
        (b5*pow(x,5.) + b4*pow(x,4.) + b3*pow(x,3.) + b2*pow(x,2.) + b1*x + b0);
 }
 return(eta);
}


double contra_eta(double speed, double ear)
{
 double a0,a1,a2,a3,x,eta;
 x = speed;
 a0 = -6.98*ear*ear + 7.35*ear - 1.09;
 a1 = 1.0*ear*ear - 1.09*ear + 0.288;
 a2 = -0.0455*ear*ear + 0.0494*ear - 0.0130;
 a3 = 0.000625*ear*ear - 0.000679*ear + 0.000177;
 if (speed < 12.)
  eta = a3*pow(12.,3.) + a2*pow(12.,2.) + a1*12. + a0;
 else
  eta = a3*pow(x,3.) + a2*pow(x,2.) + a1*x + a0;
 return(eta);
}


double preswirl_eta(double speed, double ear)
{
 double a0,a1,a2,a3,x,eta;
 x = speed;
 a0 = -5.44*ear*ear + 8.27*ear - 2.32;
 a1 = 0.85*ear*ear - 1.32*ear + 0.501;
 a2 = -0.0421*ear*ear + 0.0654*ear - 0.0248;
 a3 = 0.00064*ear*ear - 0.000997*ear + 0.000378;
 if (speed < 12.)
  eta = a3*pow(12.,3.) + a2*pow(12.,2.) + a1*12. + a0;
 else
  eta = a3*pow(x,3.) + a2*pow(x,2.) + a1*x + a0;
 return(eta);
}

double ducted_fpp_eta(double speed, double ear)
{
 double a0,a1,a2,a3,x,eta;
 x = speed;
```

```
 a0 = -1.29*ear*ear + 1.72*ear + 0.208;
 a1 = 0.0366*ear*ear - 0.0583*ear + 0.0213;
 a2 = -0.00316*ear*ear + 0.00487*ear - 0.00169;
 a3 = 0.00012*ear*ear - 0.000182*ear + 0.0000634;
 if (speed < 12.)
  eta = a3*pow(12.,3.) + a2*pow(12.,2.) + a1*12. + a0;
 else
  eta = a3*pow(x,3.) + a2*pow(x,2.) + a1*x + a0;
 return(eta);
}


double ducted_crp_eta(double speed, double PDR)
{
 double a0,a1,a2,a3,x,eta,b0,b1,b2,b3;
 x = speed;
 a0 = -0.0106*PDR + 0.762;
 a1 = 0.0144*PDR - 0.0287;
 a2 = -0.000655*PDR + 0.00141;
 a3 = 0.0000076*PDR - 0.0000199;
 eta = a3*pow(x,3.) + a2*pow(x,2.) + a1*x + a0;
 return(eta);
}


double ducted_crp_eta_low_speed(double speed, double idle_speed, double PDR,
                                double ear)
{
 double a0,a1,a2,a3,x,eta,b0,b1,b2,b3,b4,b5;
 x = speed;
 b0 = 0.00328;
 b1 = 0.0809;
 b2 = 0.0122;
 b3 = -0.000982;
 b4 = -0.0000327;
 b5 = 0.0000026;
 if (ear < .784)
 {
  a0 = -1.29*ear*ear + 1.72*ear + 0.156;
  a1 = 0.0366*ear*ear - 0.0583*ear + 0.0213;
  a2 = -0.00316*ear*ear + 0.00487*ear - 0.00169;
  a3 = 0.00012*ear*ear - 0.000182*ear + 0.0000634;
```

```
  eta = (a3*pow(idle_speed,3.) + a2*pow(idle_speed,2.)+ a1*idle_speed + a0) *
        (b5*pow(x,5.) + b4*pow(x,4.) + b3*pow(x,3.) + b2*pow(x,2.) + b1*x + b0);
 }
 else
 {
  a0 = -0.0106*PDR + 0.762;
  a1 = 0.0144*PDR - 0.0287;
  a2 = -0.000655*PDR + 0.00141;
  a3 = 0.0000075*PDR - 0.0000199;
  eta = (a3*pow(idle_speed,3.) + a2*pow(idle_speed,2.) + a1*idle_speed + a0) *
        (b5*pow(x,5.) + b4*pow(x,4.) + b3*pow(x,3.) + b2*pow(x,2.) + b1*x + b0);
 }
 return(eta);
}


double ducted_contra_eta(double speed, double ear)
{
 double a0,a1,a2,a3,x,eta;
 x = speed;
 a0 = -2.42*ear*ear + 2.0*ear + 0.476;
 a1 = -0.248*ear*ear + 0.316*ear - 0.104;
 a2 = 0.00557*ear*ear - 0.00836*ear + 0.00323;
 a3 = 0.0000977*ear*ear - 0.0000716*ear + 0.0000032;
 if (speed < 12.)
   eta = a3*pow(12.,3.) + a2*pow(12.,2.) + a1*12. + a0;
 else
   eta = a3*pow(x,3.) + a2*pow(x,2.) + a1*x + a0;
 return(eta);
}


double ducted_preswirl_eta(double speed, double ear)
{
 double a0,a1,a2,a3,x,eta;
 x = speed;
 a0 = -2.19*ear*ear + 3.18*ear - 0.305;
 a1 = 0.256*ear*ear - 0.394*ear + 0.139;
 a2 = -0.0137*ear*ear + 0.0211*ear - 0.00748;
 a3 = 0.000232*ear*ear - 0.000361*ear + 0.000129;
 if (speed < 12.)
   eta = a3*pow(12.,3.) + a2*pow(12.,2.) + a1*12. + a0;
 else
```

```
  eta = a3*pow(x,3.) + a2*pow(x,2.) + a1*x + a0;
 return(eta);
}


double fpp_J(double speed, double ear)
{
 double b0,b1,y,J;
 y = speed;
 b1 = -0.0193*ear + 0.00418;
 b0 = -0.0638*ear + 1.55;
 J = b1*y + b0;
 return(J);
}


double crp_J(double speed, double PDR)
{
 double b0,b1,y,J;
 y = speed;
 b1 = -0.00713*PDR + 0.000613;
 b0 = PDR - 0.09;
 J = b1*y + b0;
 return(J);
}


double contra_J(double speed, double ear)
{
 double b0,b1,y,J;
 y = speed;
 b1 = -0.000256*ear - 0.0119;
 b0 = -2.62*ear + 3.44;  J = b1*y + b0;
 return(J);
}


double preswirl_J(double speed, double ear)
{
 double b0,b1,y,J;
 y = speed;
 b1 = -0.00196*ear - 0.0107;
 b0 = -0.983*ear + 2.48;
```

```
 J = b1*y + b0;
 return(J);
}

double ducted_fpp_J(double speed, double ear)
{
 double b0,b1,y,J;
 y = speed;
 b1 = -0.000407*ear - 0.0129;
 b0 = -18.5*ear*ear + 26.10*ear - 7.42;
 J = b1*y + b0;
 return(J);
}

double ducted_crp_J(double speed, double PDR)
{
 double b0,b1,y,J;
 y = speed;
 b1 = -0.0245*PDR + 0.0228;
 b0 = 2.16*PDR - 1.68;
J = b1*y + b0;
 return(J);
}

double ducted_contra_J(double speed, double ear)
{
 double b0,b1,y,J;
 y = speed;
 b1 = 0.00278*ear - 0.0131;
 b0 = -70.1*ear*ear + 70.7*ear - 15.5;
 J = b1*y + b0;
 return(J);
}

double ducted_preswirl_J(double speed, double ear)
{
 double b0,b1,y,J;
 y = speed;
 b1 = 0.00122*ear - 0.0107;
```

```
 b0 = -5.2*ear*ear + 6.97*ear - 0.651;
 J = b1*y + b0;
 return(J);
}
```

Prop_Performance for Amphibious Ship Design

/* This module is designed to provide performance estimate for two types of LX propulsors. It takes as input the propulsor type of interest, propeller geometry information generated by the function prop_design and speed for which performance is required. It returns the QPC and RPM of the selected propulsor at that speed. Functions are included which invoke correlations for propeller performance based on data collected from the Propeller Lifting Line computer program. */

```
#include "prop_lx.h"

void prop_performance(int type_props, int num_cruise_prop, double speed, double
                      idle_speed, double EAR, double *QPC, double *rpm)
{
 double thrust_ded = 0.905;     /* 1-t */
 double wake_frac = 0.965;      /* 1-w */
 double Va;
 double Dp;
 Dp = 16.;
 Va = speed * 1.68781 * wake_frac;
 if(num_cruise_prop == 1)
 {
   speed = 1.6 * speed;
   Va = 1.6 * Va;
   *QPC = (efficiency(speed, idle_speed, EAR, type_props) * thrust_ded) / wake_frac;
   if(type_props == 2 && speed < idle_speed)
   {
    speed = idle_speed;
    Va = speed * 1.68781 * wake_frac;
    *rpm = (Va * 60.)/(J(speed, EAR, type_props) * Dp);
   }
   else
    *rpm = (Va * 60.)/(J(speed, EAR, type_props) * Dp);
 }
 else
 {
```

```
    *QPC = (efficiency(speed, idle_speed, EAR, type_props) * thrust_ded) / wake_frac;
    if(type_props == 2 && speed < idle_speed)
    {
     speed = idle_speed;
     Va = speed * 1.68781 * wake_frac;
     *rpm = (Va * 60.)/(J(speed, EAR, type_props) * Dp);
    }
    else
     *rpm = (Va * 60.)/(J(speed, EAR, type_props) * Dp);
  }
  return;
}


/* This function returns the open water efficiency of a selected LX prop. */

double efficiency(double speed, double idle_speed, double EAR, int type_props)
{
 double eta;
 if(type_props == 1)                /* FPP */
 {
  eta = fpp_eta(speed, EAR);
  return(eta);
 }
 if(type_props == 2)                /* CRP */
 {
  if(speed < idle_speed)
   eta = crp_eta_low_speed(speed, idle_speed, EAR);
  else
   eta = crp_eta(speed, EAR);
  return(eta);
 }
return(0);
}


/* This function returns the advance coefficient at a particular speed for the LX. */

double J(double speed, double EAR, int type_props)
{
 double J;
 if(type_props == 1)                /* FPP */
 {
```

```
   J = fpp_J(speed, EAR);
   return(J);
  }
  if(type_props == 2)                   /* CRP */
  {
   J = fpp_J(speed, EAR);
   return(J);
  }
 return(0);
 }


double fpp_eta(double speed, double ear)
{
 double a0,a1,a2,a3,x,eta;
 a0 = 0.463*ear*ear - 1.2*ear + 1.33;
 a1 = -0.272*ear*ear + 0.424*ear - 0.165;
 a2 = 0.0363*ear*ear - 0.0567*ear + 0.0221;
 a3 = -0.00113*ear*ear + 0.00176*ear - 0.000689;
 if (speed < 12.)
  eta = a3*pow(12.,3.) + a2*pow(12.,2.) + a1*12. + a0;
 else
  eta = a3*pow(speed,3.) + a2*pow(speed,2.) + a1*speed + a0;
 return(eta);
}


double crp_eta(double speed, double ear)
{
 double a0,a1,a2,a3,x,eta;
 x = speed;
 a0 = 0.463*ear*ear - 1.2*ear + 1.278;
 a1 = -0.272*ear*ear + 0.424*ear - 0.165;
 a2 = 0.0363*ear*ear - 0.0567*ear + 0.0221;
 a3 = -0.00113*ear*ear + 0.00176*ear - 0.000689;
 eta = a3*pow(x,3.) + a2*pow(x,2.) + a1*x + a0;
 return(eta);
}


double crp_eta_low_speed(double speed, double idle_speed, double ear)
{
 double a0,a1,a2,a3,x,eta,b0,b1,b2,b3,b4,b5;
```

```
 x = speed;
 b0 = 0.00328;
 b1 = 0.0809;
 b2 = 0.0122;
 b3 = -0.000982;
 b4 = -0.0000327;
 b5 = 0.0000026;
 a0 = 0.463*ear*ear - 1.2*ear + 1.278;
 a1 = -0.272*ear*ear + 0.424*ear - 0.165;
 a2 = 0.0363*ear*ear - 0.0567*ear + 0.0221;
 a3 = -0.00113*ear*ear + 0.00176*ear - 0.000689;
 eta = (a3*pow(idle_speed,3.) + a2*pow(idle_speed,2.) + a1*idle_speed + a0) *
(b5*pow(x,5.) + b4*pow(x,4.) + b3*pow(x,3.) + b2*pow(x,2.) + b1*x + b0);
 return(eta);
}


double fpp_J(double speed, double ear)
{
 double b0,b1,y,J;
 y = speed;
 b1 = -4.18*ear*ear + 6.28*ear - 2.36;
 b0 = 102*ear*ear - 154*ear + 59.7;
 J = b1*y + b0;
 return(J);
}
```

Appendix Fourteen

Computer Routines for Predicting Propulsor Size and Weight

```
/* This function provides the size (volume) required (if any), and the weight of a
selected propulsor. Correlations are used for prop diameter vs weight, internal volume
required for CRP controls vs CRP prop weight, and waterjet weight and volume
characteristics of a KaMeWa model 250SII waterjet propulsion unit. */

#include "propmain.h"

void prop_size(int type_prop, double Dp, double *weight_prop, double *vol_prop)
{
 if(type_prop == 9)     /*waterjet*/
 {
  *weight_prop = 119.5;
  *vol_prop = 4894.;
  return;
 }
 if(type_prop == 1 || type_prop == 5)          /* fixed pitch or ducted fpp*/
 {
  *weight_prop = (8.4*Dp*Dp*Dp)/2240.;
  *vol_prop = 0.;   if(type_prop == 5)
   *weight_prop = *weight_prop + (5.78*Dp*Dp*Dp)/2240.;
  return;
 }
 if(type_prop == 2 || type_prop == 6)     /*CRP or ducted CRP*/
 {   *weight_prop = (1.25*(13.8*Dp*Dp*Dp))/2240.;
  *vol_prop = 800.;
  if(type_prop == 6)
   *weight_prop = *weight_prop + (5.78*Dp*Dp*Dp)/2240.;
  return;
 }
 if(type_prop == 3 || type_prop == 4 || type_prop == 7 || type_prop == 8)
 {
  *weight_prop = (12.*Dp*Dp*Dp)/2240.; /*contrarotating or fpp/stator*/
  *vol_prop = 0.;
```

```
    if(type_prop == 7 || type_prop == 8)
      *weight_prop = *weight_prop + (5.78*Dp*Dp*Dp)/2240.;
    return;
  }
  return;
}
```