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HYDRODYNAMIC DESIGN CONSIDERATIONS FOR THE CONTROLLABLE-PITCH PROPELLER FOR THE GUIDED MISSILE FRIGATE

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ABSTRACT

The restrictions imposed on a propeller design by the controllable-pitch feature can be severe. In the case of the Guided Missile Frigate (FFG), the constraints were a controllable-pitch propeller absorbing 40,000 shaft horsepower (SHP), with distinct mission performance requirements related to propeller efficiency and cavitation performance. The hydrodynamic design of the FFG propeller involved "trade-offs" between full-power and design-endurance speed and considerations of blade strength, vibration, cavitation characteristics, and propeller blade spindle torque. Model experiments confirmed that, considering the constraints imposed on the design, use of the best available design procedures and analytical techniques has resulted in a propeller for the FFG which has good overall performance.

INTRODUCTION

CONTROLLABLE-PITCH PROPELLERS—GENERAL

TO FULLY APPRECIATE PROBLEMS associated with the hydrodynamic design of the Guided Missile Frigate (FFG) propeller, it has been necessary to outline in general the problems with high-power controllable-pitch propellers and the capabilities for attacking these problem areas. The relative importance of the capabilities and the manner in which they are used in the specific Guided Missile Frigate design will be apparent in subsequent sections.

Controllable-pitch (C-P) propellers have a wide application to naval ships. They have been installed on tugs, mine-sweepers, landing craft, and high-speed combatant ships, including patrol gun-boats and destroyer escorts. C-P propellers on surface ships offer advantages for craft with multiple mission requirements. Propeller-pitch control enables ships to operate efficiently at a variety of propeller pitch and RPM conditions with a minimum of cavitation, and it furnishes backing capability without shaft reversal. Both are ideally suited for power plants which have high efficiencies over limited RPM ranges and for high-speed craft in which weight is critical with shaft reversal gearing to be avoided if possible.

The disadvantages of incorporating C-P propellers into any ship powering system can be considered to be in two specific categories: 1) those problems associated with C-P propellers in particular, and 2) those problems characteristic of any propeller application, fixed-pitch or otherwise, but somewhat worsened by the geometric limitations of C-P propeller configurations.

Under the first category, the *main* problems associated with C-P propellers are: cost, maintenance, reliability, optimization, and control.

The acquisition cost of a C-P propeller can be assumed to be several times that of a comparably sized fixed-pitch propeller. The maintenance cost differential must be regarded as even more significant since complete overhaul is required, on the average, every two years for hydraulically actuated C-P propellers.

A rather low reliability rating has been assigned to C-P propeller systems, but it should be pointed out that this is probably not the result of a lack of mechanical technology, but rather a lack of hydrodynamic technology. Until such time that accurate estimates can be made of the mean and unsteady loading on C-P propellers, it is not reasonable to expect that satisfactory machinery can be designed to deliver efficient and reliable performance. The shortage of full-scale and model C-P propeller information concerning "off-design" propeller performance has made it necessary to incorporate conservative safety factors into present day C-P designs. These result in excessive propeller/hub weights and non-optimum blade configurations. In propeller systems involving more than one C-P propeller, ship control is more difficult because of the inability to set and determine proper blade pitch. All these problem areas—reliability, control, and propeller/mechanism optimization—are due directly to the overall lack of propeller performance data to establish appropriate design criteria and adequate control systems.

The problems of propeller blade unsteady loading, cavitation and erosion are problems of fixed-pitch and controllable-pitch propellers alike. These problems are somewhat amplified in the case of the C-P propeller due to the geometric limitations placed on C-P propellers. To attain negative pitches for the backing mode, C-P propellers normally pass through zero pitch. This restriction limits the maximum blade area and leads, in general, to blade shapes which are narrow at the root and wide in the tip region. Neither the total blade area limitation nor the characteristic C-P propeller chord length distribution are favorable for delaying or preventing blade cavitation and erosion. C-P propellers which are designed to absorb high power and/or operate in a significant wake generally have thick blade root sections for strength purposes. The combination of small blade chord and large root thickness produces blade root sections with high thickness/chord ratios which are subject to cavitation and erosion, particularly for propellers applied to high-speed craft.

From the standpoints of vibration, blade stress, cavitation, and erosion, the C-P propellers presently proposed for application to high speed hull forms are at a distinct disadvantage. They are generally installed at a sizable shaft angle, and this angle, plus the hull slope in the region of the propeller, produces a considerable "upwash" at the propeller plane. The nature of this upwash tends to vary the blade loading considerably during a propeller revolution. Blade sections are subjected to wide angle of attack variations, particularly at the blade root where the thickness/chord ratios already present a cavitation problem. In addition, C-P propellers tend to have the blade area and loading concentrated toward the blade tip regions. In combination with the presence of a more severe longitudinal wake pattern near the hull, the C-P propeller is more susceptible to tip vortex cavitation inception.

Within the Navy considerable effort has been directed toward improving C-P propeller design and performance. Research has proceeded in areas of model and full-scale propeller performance evaluation.

C-P propeller model series have been evaluated [1] to determine steady-state design and "off-design" operating performance as functions of advance condition, blade pitch, blade area, number of blades, and propeller blade skew. C-P propeller blade spindle moment has been determined experimentally as a function of propeller geometry and operating conditions [2][3].

Model experiments are continuing to determine the best root section thickness distribution to delay C-P propeller blade root cavitation and minimize erosion.

Model propeller design and evaluation is currently underway to determine the potential hydrodynamic advantages of employing staggered blades in order to improve propeller blade geometry and cavitation characteristics for high power C-P propeller applications.

Full-scale C-P propeller performance evaluation has been or is being carried out on two Destroyer Escorts, and this information base will be expanded further as the result of future trials when the DD 963 Class destroyer and the Guided Missile Frigate go to sea. Coordinated model evaluation research and corresponding full-scale development of C-P propeller systems have progressed well. With available and anticipated full-scale trial data for intermediate and high power C-P systems, the necessary full-scale data will be realized. The disadvantages of C-P propeller systems (i.e., cost, maintenance, reliability, optimization, and control) should be minimized, making them viable and dependable competition for fixed-pitch propellers.

PROPELLER DESIGN PROCEDURES

Current established propeller design procedures at the Naval Ship Research and Development Center

(NSRDC) involve the use of lifting line and lifting surface mathematical models. Lifting line theory based on the method of Lerbs [4] is used to iterate to a given absorbed power for a prescribed blade radial load distribution and to define the induced axial and tangential flow velocities at the propeller plane. To account for finite blade area and thickness and to enable design for a prescribed blade pressure distribution, lifting surface calculations are made beginning with, and incorporating, final lifting line calculation data. The lifting surface calculation procedures are based on analytical methods developed by Pien and Cheng [5] to account for blade surface loading and by Kerwin and Leopold [6][7] to consider blade thickness effects. Both blade area and thickness considerations result in significant blade section pitch and camber adjustments which are necessary to achieve desired performance for the three-dimensional blade design. These adjustments are made on the final lifting line data using two-dimensional airfoil characteristics as the baseline case.

Although lifting line and lifting surface calculation procedures are the basis of design capability, other procedures and established data are necessary for their proper utilization. Considerations which either enter into lifting line/lifting surface design or which are carried out in parallel are as follows:

1) Model bare hull and appendage resistance experiments.

2) Model powering experiments with stock propellers of known open water performance. These experiments yield thrust deduction, nominal wake fraction, and hull efficiency.

3) Detailed hull wake surveys which map the axial and tangential flows in the propeller plane. Computerized techniques to analyze the harmonic content of such wake distributions.

4) Programs to calculate unsteady propeller loading based on propeller geometry and harmonic content of nonuniform wakes.

5) Beam theory and finite element calculation technique for estimating stress levels in propeller blades under mean loading.

6) Yield stress and fatigue data for materials based on sample destruction experiments in conditions of mean and periodic applied loadings.

7) Cavitation inception curves which predict the onset of cavitation and the type of cavitation based on section shape, loading, and operating conditions.

8) Cavitation tunnel experimental techniques for final propeller design evaluation under simulated operating conditions.

9) A wide base of reliable experimental propeller and hull data for check and comparison at various levels throughout the design process.

Guided Missile Frigate Propeller Requirements

The ship hull, power train characteristics, and ship mission requirements traditionally govern propeller selection and design. Therefore, with the exception of general propeller performance characteristics considered during preliminary ship design, propeller restrictions do *not* drive the ship design. When the time arrives for detailed propeller design, the designer is usually "locked" into a given hull, appendage and shafting arrangement, a Shaft Horsepower—RPM relationship, probably a given propeller diameter or limited diameter range, and frequently, propulsive requirements for several operational modes. With present trends toward increased ship speed and absorbed horsepower, it becomes more difficult to generate propeller blade designs which have good hydrodynamic performance (i.e., propulsive and cavitation performance) and which also have adequate structural integrity in view of high mean and unsteady stress levels.

Design and performance requirements for the Guided Missile Frigate propeller were representative of high power naval application requirements and were stringent in that the FFG propeller was to have controllable-pitch blades.

The FFG propeller would be five-bladed and absorb 40,000 SHP at specified displacement, trim, and hull surface conditions. Propeller tip diameter would be 16.50 feet and hub diameter would tentatively be 4.95 feet. Performance requirements were given for full power and endurance operating conditions, and these are listed in TABLE 1 along with their respective weighting factors.

TABLE I

FFG PROPELLER PERFORMANCE REQUIREMENTS

Requirement	Weighting Factor
1. Propeller efficiency at full power ≥ 0.69	40-50%
2. Propeller efficiency at endurance ≥ 0.71	30%
3. Delay of cavitation inception: erosion	10-15%
4. Ship, power plant, and C-P propeller considerations **	8-10%*
5. ASW warfare cavitation inception considerations: noise; delay of tip vortex	2-5%*

* to the extent possible without compromising full power performance.

** reducing: hull and machinery vibrations, blade spindle loads, and power plant transient and non-transient torque loads.

GUIDED MISSILE FRIGATE PROPELLER DESIGN

Full Power Considerations

With prime importance assigned to FFG propeller efficiency at the full power operating condition, it was necessary in the initial phase of the design to determine the ranges of blade geometry and radial loading distributions which would yield a minimum propeller efficiency of 0.69 at full power. This was accomplished by generating a series of propeller designs for full power with the lifting line calculation method. Parameters entering into the designs and which were varied throughout their practical range were: a) blade area, b) blade thickness distribution, c) hub and tip pitch reduction, and d) radial location of maximum pitch. Three blade area distributions (Figure 1) and three radial thickness distributions (Figure 2) for each blade area were considered. For each blade area/thickness configuration, a number of pitch distributions were evaluated. A typical example of the lifting line design analysis for one pitch distribution is shown in the working plot of Figure 3.

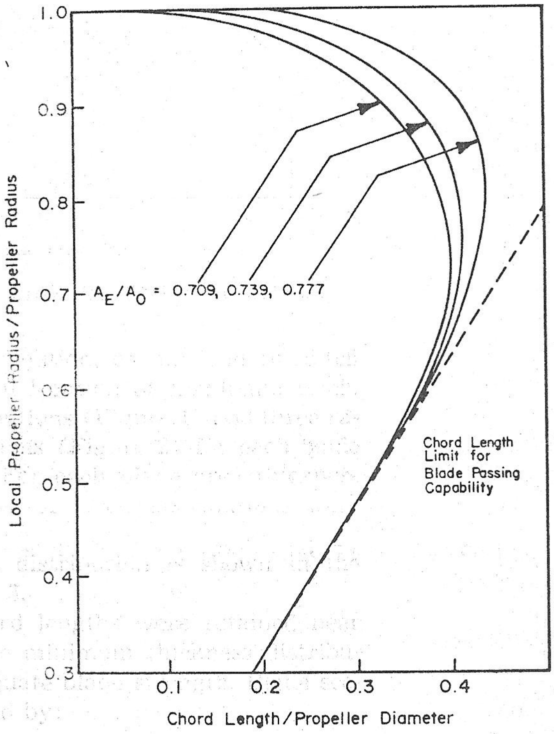


Figure 1 — Range of Blade Areas

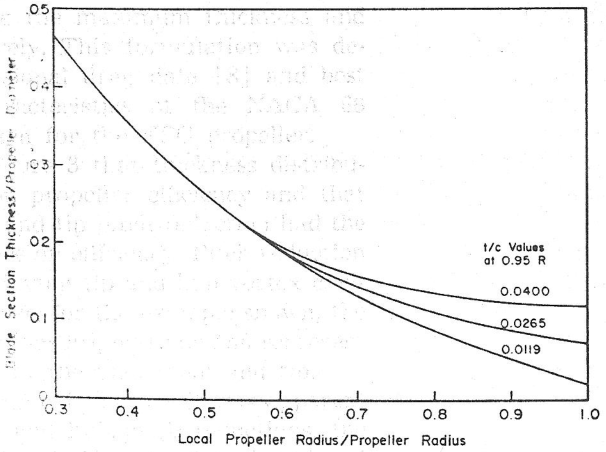


Figure 2 — Range of Maximum Section Thicknesses for Each Blade Area Ratio Considered

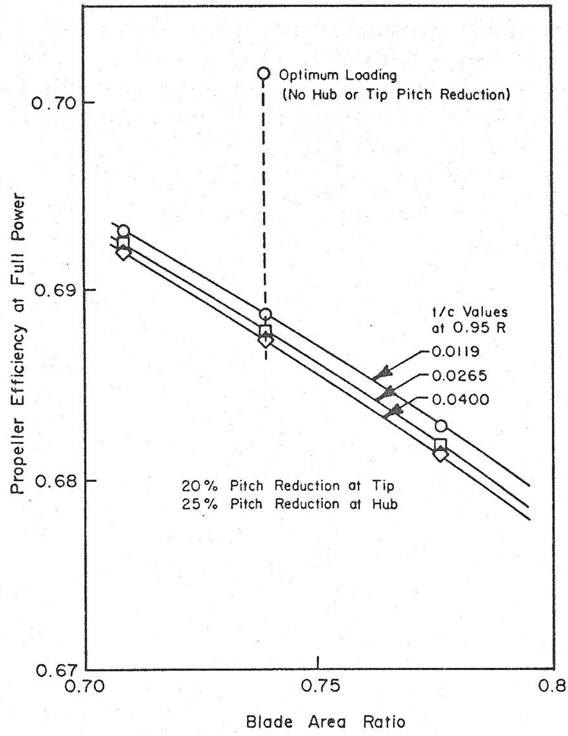


Figure 3 — Predicted Propeller Efficiency at Full Power

Maximum blade chord lengths were retained near the hub along with the minimum thickness distribution necessary for adequate blade strength. Blade section drag was estimated by:

$$C_D = 0.008[1.0 + 1.25(t/c) + 125.0(t/c)^4]$$

where "t" and "c" are the maximum thickness and chord length, respectively. This formulation was derived from two dimensional drag data [8] and best approximates the characteristics of the NACA 66 thickness sections chosen for the FFG propeller.

It can be seen in Figure 3 that thickness distribution had little effect on propeller efficiency and that blade area and/or hub and tip pitch reduction had the most significant influence on efficiency. Pitch reduction is recommended for delaying tip and hub vortex cavitation inception. However, for the example shown, the hub and tip pitch reductions are extreme and represent almost total unloading at the blade root and tip.

From the initial design calculations it was apparent that, for moderate tip and hub pitch reductions, the blade area ratio for the FFG propeller should *not* exceed 0.74 in order that required propeller efficiency be available at the full-power condition.

Since, from viscous considerations, theoretical efficiency increases with decreasing blade area, it was necessary in evaluating the remaining candidate designs to rely on cavitation and thrust breakdown considerations. No reliable procedures for predicting thrust breakdown due to cavitation were applicable to the relatively narrow ranges of propeller geometry under consideration. Therefore, it was necessary to make the predictions based on extensive model propeller experimental data. A series of five-bladed research propellers which were geometrically similar in blade area, pitch distribution, and section shape to the probable FFG design had been evaluated [9] in water tunnel experiments. Each had been tested through the point of thrust breakdown. These data were used in conjunction with cavitation inception diagrams derived by Brockett [10]. A back analysis of the experimental data showed that the point of propeller thrust breakdown coincides with the inception of propeller "back bubble" cavitation. Further, the predicted inception of "back bubble" cavitation from the diagrams was conservative and thrust breakdown (back bubble) did not occur until operating local section cavitation numbers, σ_x, were 10% to 20% lower than predictions. Figure 4 shows a representative plot made during the cavitation analysis. The envelope of the cavitation inception diagram predicts "back sheet," "back bubble," and face cavitation as a function of section operating cavitation number and angle of attack. The shape of the envelope is determined analytically using the thickness-chord ratio, the thickness distribution along the chord, the camber distribution, and the theoretical lift of the two-dimensional section. For a given propeller blade, each spanwise section under consideration would have a specific inception diagram corresponding to its particular geometry. In the example of Figure 4, the operating characteristics of the specific FFG propeller radial section have been superimposed on the diagram along with the predicted region of thrust breakdown. Dotted lines for the full power and endurance operating conditions show that during propeller revolution, a blade section is subjected to an angle of attack variation and a change in the total resultant velocity into the section.

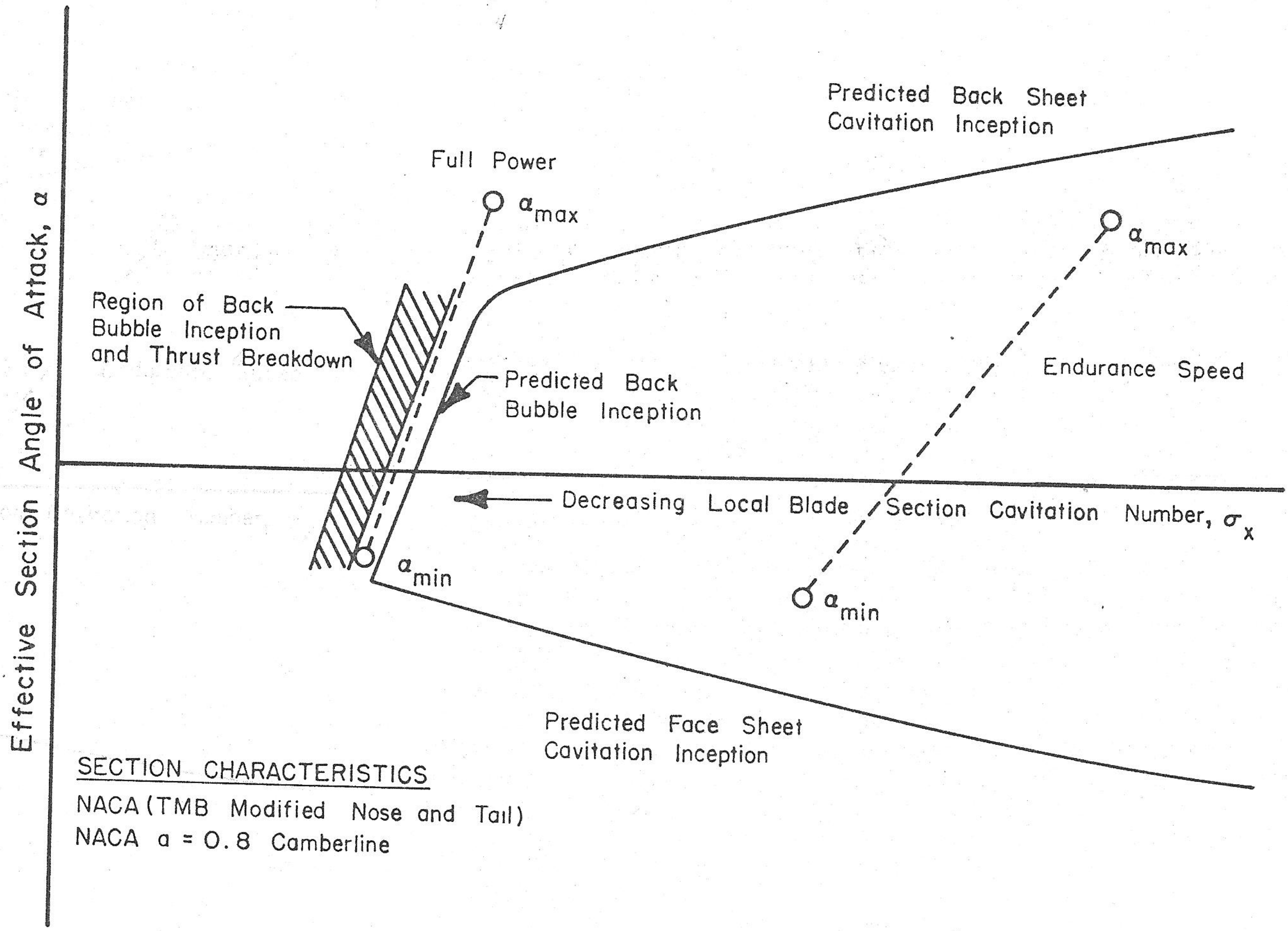


Figure 4—Typical Cavitation Inception Curve for a Specific Camber Ratio and Thickness Ratio—FFG Propeller

By using working plots for each radial section as in the example of Figure 4, the thickness/chord distribution was determined for the FFG propeller blade. The prime criterion entering into the selection was avoidance of thrust breakdown. In areas of the blade where adjustment of the thickness/chord distribution did *not* compromise the thrust breakdown restriction, final values were selected to insure "back sheet" cavitation as opposed to face cavitation. Calculated angle of attack variations indicated that it would be impossible to prevent the inception of both face and back sheet cavitation for some blade radii. The final blade thickness distribution and chord distribution lay near the midrange of the limits investigated in both thickness and chord shown in Figures 1 and 2.

Endurance Operation

The FFG propeller design requirements assigned major importance to the propeller efficiency at endurance (20 knot) operation. To insure a minimum propeller efficiency of 0.71 at 20 knot operation, a second series of propeller designs was carried out. Blade chord and thickness distributions had already been established from full power operating requirements. Parameters to be varied in the endurance designs were propeller RPM and blade hub and tip pitch reduction (the limiting values of which had already been established). The series of 20 knot propeller designs, each with a nonvarying nominal tip pitch reduction, was generated for a range of propeller RPM. The shaft horsepower/RPM values determined for each design were then evaluated on a basis of main propulsion plant fuel consumption. Engine performance curves for the LM 2500 gas turbine furnished estimated fuel consumption data based on shaft horsepower and RPM variables. Therefore, for each 20 knot propeller design, a fuel consumption rate could be determined. Based on minimum fuel consumption criteria and calculated propeller efficiencies at endurance speed, the RPM was selected to be 111.6.

Since propeller efficiency had been proven to be quite insensitive to blade-hub pitch reduction, another series of propeller lifting line propeller designs was generated. Each design had the given blade chord and thickness distributions already established, the optimum RPM, a set nominal hub pitch reduction of 19% (from the maximum), and varying tip pitch. Calculated propeller efficiencies as a function of pitch reduction for each design are shown in Figure 5. Considering efficiency criteria at both full power and endurance operation, blade tip pitch reduction was chosen to be approximately 13% and hub pitch reduction set at 19%.

Propeller Blade Skew

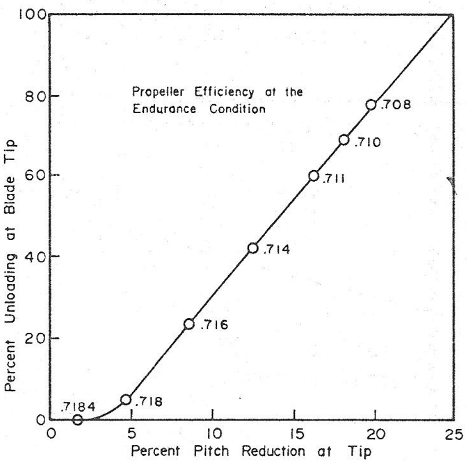
A characteristic of recent NAVY propeller designs has been the incorporation of significant blade skew. Lifting surface design techniques developed within the last 15 years have made it possible to design propellers with skew which will meet desired performance criteria.

Blade skew offers improved cavitation performance [9]. Depending on the specific wake distribution, reduced unsteady blade loadings can be realized for skewed blades versus nonskewed blades. Depending on the manner in which unsteady individual blade forces tend to sum during propeller revolution, reduction in unsteady propeller bearing forces and moments usually result through the application of skewed blades.

High blade skew, i.e., a large degree of tip sweepback, has not been considered for C-P propellers for obvious reasons. Skew serves to displace blade tip sections axially and circumferentially from the radial reference location of blade root sections. An obvious consequence in C-P propellers would be large moments about the blade spindle axis resulting from displacement of the center of hydrodynamic loading from the spindle axis.

Moderate skew was applied to C-P propeller blades in the design of the DD-963. Tip sweepback was approximately 20 degrees and model experiments showed that throughout the anticipated operating range peak spindle torque levels were acceptable. It should be emphasized that even in the absence of blade skew, C-P propeller blades experience significant spindle torque. The reasons for this are that during "off-design" operations (blade pitch or advance), the blade center-of-pressure moves considerably in the chordwise direction and can change the spindle torque by an order of magnitude or more in the normal C-P operating range.

In the case of the FFG propeller, a nonskewed blade probably would have been acceptable and would have met the design requirements. Several factors, however,



$$\text{Percent Unloading at Blade Tip} = \frac{\tan\beta_i\ (\text{OPT}) - \tan\beta_i\ (\text{TIP})}{\tan\beta_i\ (\text{OPT}) - \tan\beta} \times 100$$

where

$$\text{Percent Pitch Reduction} = \frac{(P/D)_{\text{MAX}} - (P/D)_{\text{TIP}}}{(P/D)_{\text{MAX}}} \times 100$$

β_i (OPT) = Tip Hydrodynamic Pitch Angle (Without Pitch Reduction)

β_i (TIP) = Tip Hydrodynamic Pitch Angle (Reduced Pitch)

β = Propeller Tip Advance Angle

P/D = Propeller Pitch/Propeller Diameter

Figure 5—Effect of Blade Tip Unloading on Propeller Efficiency, Endurance Operating Condition

made blade skew an attractive complement in the design. Any delay in cavitation inception or reduction in the extent of existing cavitation would be desirable from ASW considerations. Unsteady blade loadings resulting from operation behind struts should be reduced with skew. Also, recent spindle moment measurements on a series of propellers showed that the sensitivity, with respect to propeller advance, of hydrodynamic spindle moment could be reduced with a form of "balanced skew" [3]. In such a skew distribution, blade sections are moved forward along the pitch helix at stations near the propeller hub and moved aft in the tip region. The balanced skew distribution selected for the FFG propeller is shown in Figure 6. The effect of employing such a skew is to balance the blade loading about the spindle axis at design and off-design operating conditions. Such a distribution also allows greater effective tip skew for vibratory considerations without large displacement of blade sections from the spindle axis.

Based on experimental results, predictions were made of the FFG propeller hydrodynamic spindle torque over a range of advance. These predictions are shown in Figure 7 and assumed the cases of balanced skew and no skew. The predictions assume that throughout the range of advance shown the blade pitch setting was constant and near the final design value. It can be seen that spindle torque is less sensitive to changes in advance with balanced skew. Experimental evaluation of a model FFG propeller was carried out subsequent to the design. Good agreement between prediction and experiment occurred at the full-power design advance coefficient.

Propeller Blade Stress and Unsteady Forces

Throughout the design process leading to the selection of FFG propeller blade geometry, calculations were made of the mean and unsteady hydrodynamic forces and moments to which the blades and total propeller assembly would be subjected. Steady blade moments and consequent stresses were determined from modified beam theory. At later stages of the design when final blade geometry was determined, mean stress levels were also determined from finite element calculation techniques.

Unsteady blade stresses were estimated from calculations of the unsteady hydrodynamic blade loading. Calculation of unsteady blade loading [11] requires approximate blade geometry and an accurate definition

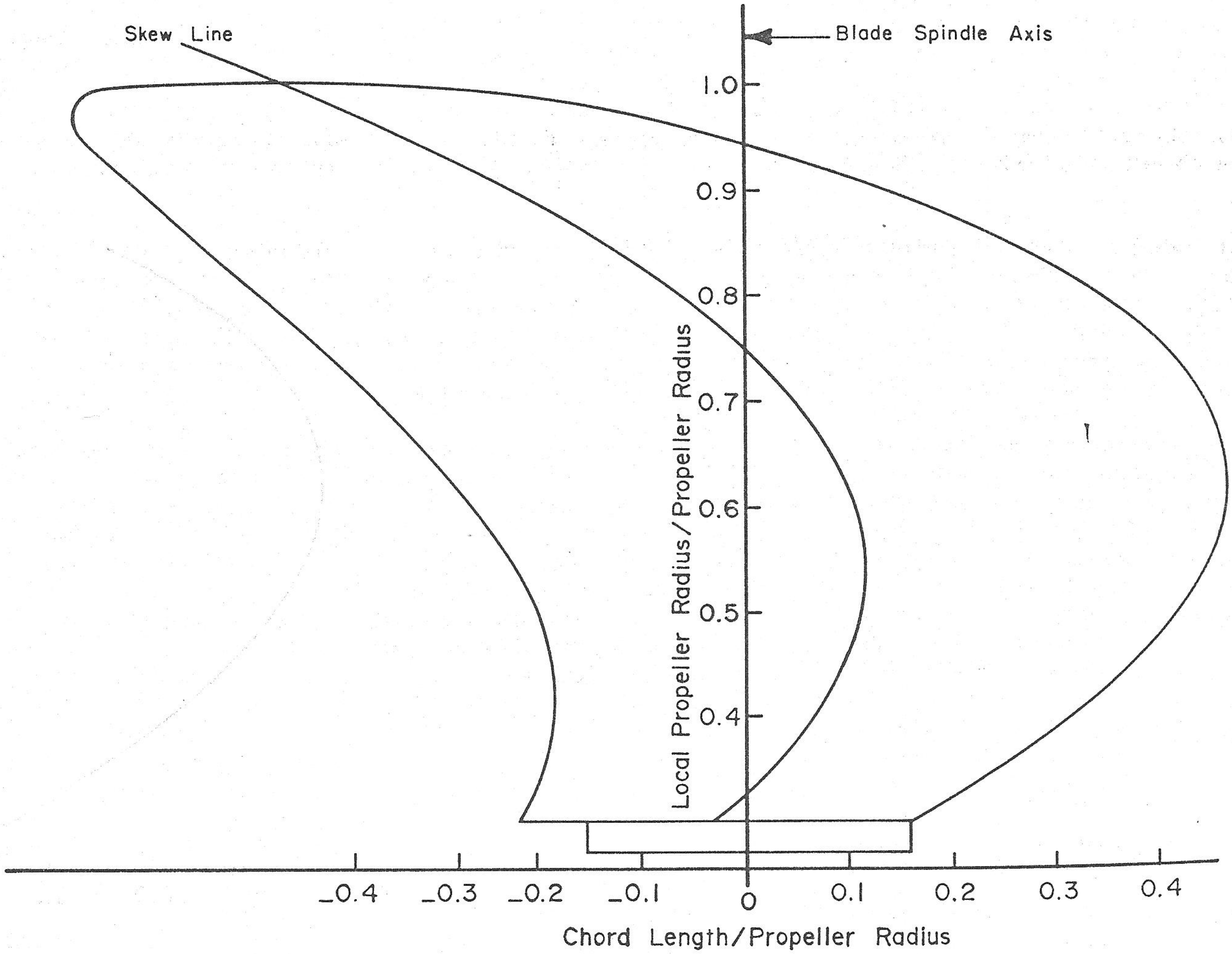


Figure 6—FFG Propeller, Expanded Blade Outline

of the harmonic content of hull and appendage wake at the propeller plane. Estimates of the resulting unsteady blade stresses are then derived by assuming the ratio of unsteady stress to steady stress to be equal in magnitude to the ratio of unsteady bending moment to steady bending moment. The maximum alternating and steady stresses determined for the FFG propeller blades are shown in Figure 8. They have been superimposed on a modified Goodman diagram. This diagram indicates the yield point (under steady load) and the fatigue failure points (in sea water) for the Nickel-Aluminum-Bronze alloy proposed for propeller construction material. In constructing the diagram, it has been assumed that unsteady stress and steady stress are additive with regard to material failure and that the safe region for any combination of the two values should lie well beneath the desired cycle life. The diagram indicates that, for the material considered and the peak stresses anticipated, the FFG propeller will *not* experience elastic or fatigue failure.

The method for calculating unsteady blade loadings also yields the unsteady propeller forces and moments. These are derived by summing, in phase, the individual blade contributions as a function of circumferential location. The unsteady propeller forces and moments are transmitted through the propeller shafting and bearings and often produce severe vibration and noise. Limits on the unsteady thrust is approximately 1.5% of the mean full-power thrust, respectively. Unsteady propeller thrust and torque values calculated for the FFG design were 1.0% of the mean full-power thrust and 0.9% of the mean full-power torque, respectively.

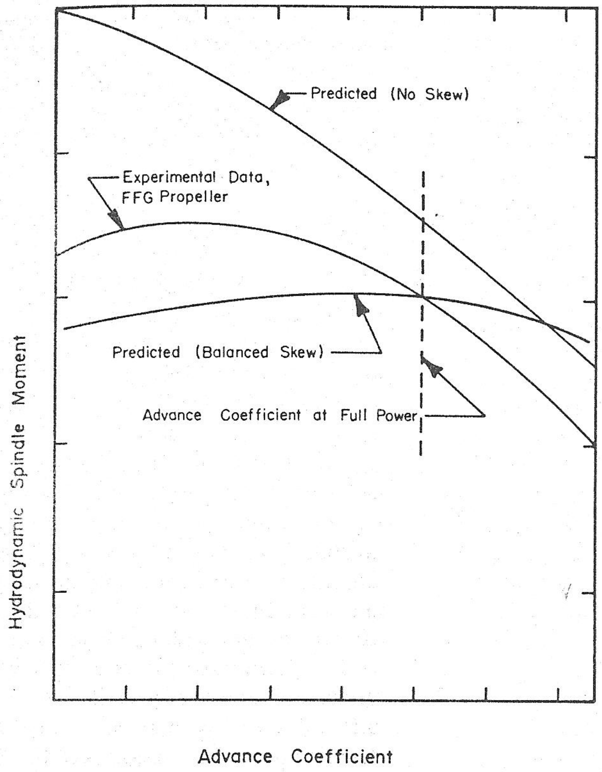


Figure 7—FFG Propeller Spindle Moment

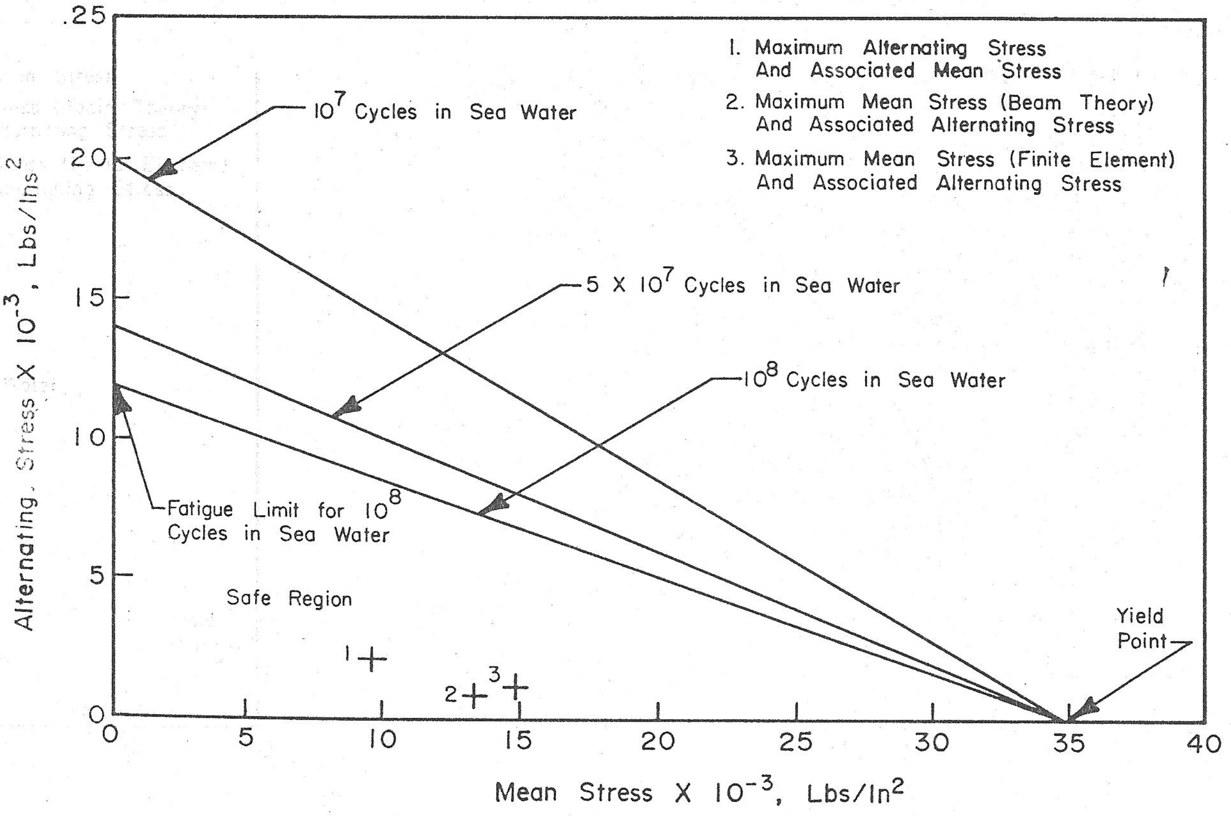


Figure 8—Design Stress on a Modified Goodman Diagram, FFG Propeller

Selection of Final Design

As previously discussed, the majority of propeller preliminary design is centered around lifting line calculation techniques. Lifting surface calculations are normally carried out near the conclusion of the design process. They are necessary to define accurately the adjustments and distortions to the blade shape which are necessary to achieve (in three-dimensional finite area blades) the spanwise and chordwise loadings which were assumed in two-dimensional flow. The time and expense involved in making lifting surface calculations usually limits use of the formal procedures to the final stages of propeller design. In the earlier design phases, approximate procedures are available [12] for determining lifting surface corrections to blade pitch and camber.

In the case of the FFG propeller, preliminary estimates of the final design geometries for the endurance design and full power design showed that the two propellers were very similar in final prescribed pitch. This had been anticipated due to the extent of reduction in operating advance coefficient from endurance speed to full power speed apparent in the "stock" propeller powering tests.

Final lifting surface calculations were carried out for the endurance and full-power designs. Resulting pitch distributions for the two designs were almost identical, and the camber distribution for the endurance design, although smaller in magnitude than that of the full-power design, was within 10% of the full-power camber values. The question then became which would be the better overall design for the FFG. Calculations were carried out with an inverse propeller performance program developed at the Massachusetts Institute of Technology [13]. The cases considered were the endurance design operating at the full-power operating condition and the full-power design operating at endurance condition. It was concluded that both propeller designs would meet operating requirements at both advance conditions and that the effect of the slight camber differences between the two designs was insignificant. From other considerations it was determined that the endurance design would be less subject to face cavitation at the endurance condition on the simple basis of its slightly smaller camber. Therefore, the endurance design was recommended for model construction and experimental evaluation.

TABLE 2

COMPARISON OF PREDICTED AND EXPERIMENTAL FFG PROPELLER POWERING PERFORMANCE

	ENDURANCE	FULL POWER
Ship Speed	0.0%	−0.4%
Effective Horsepower, P_E	+1.9%	−1.3%
Shaft Horsepower, P_D	−1.2%	0.0%
Propeller RPM	−0.5%	−0.8%
Advance Coefficient, J	−1.9%	−1.9%
Thrust Deduction Factor, $1 - t$	−0.5%	−0.5%
Wake Fraction, $1 - W$	−2.5%	−2.1%
Propeller Efficiency, e_p	+0.3%	−1.0%
Propulsive Coefficient, $\eta_D = \frac{EHP}{SHP}$	+3.1%	−1.4%

$$\frac{\text{EXPERIMENTAL} - \text{PREDICTED}}{\text{PREDICTED}} \times 100\%$$

Experimental Evaluation

The model propeller recommended for the FFG was evaluated in open water, in powering tests behind the FFG model hull, and in cavitation experiments conducted in a variable pressure water tunnel. Data from the powering tests are shown in TABLE 2 as percentage differences from the predicted performance. Cavitation tests showed that the extent and type of blade cavitation at full power was near that predicted, and that at the *simulated* full-power operating conditions the propeller suffered *no* thrust breakdown due to cavitation.

It was concluded that the design, as specified, produced good overall performance in the model evaluation. The design was consequently recommended to the manufacturer responsible for Guided Missile Frigate propeller construction.

CONCLUSIONS

The details which entered into the hydrodynamic design of the C-P propeller for the Guided Missile Frigate have been outlined and described. The manner in which this design was governed by the C-P feature, by mission requirements, and by ship and power plant considerations has been emphasized.

It has been the intent of this paper to show how ship mission and performance requirements may complicate a propeller selection much as they can complicate the design of other ship subsystems. Further, it has been emphasized that the controllable-pitch feature can place addditional constraints on propeller hydrodynamic design.

Model evaluation of the FFG propeller showed that, considering the constraints imposed, a propeller design with acceptable overall performance was developed with the tools available. However, it should be further emphasized to the Naval Engineering Community that those tools available, while adequate for the specific requirements of the FFG propeller design, may not be adequate in the future under the constraints of differing requirements.

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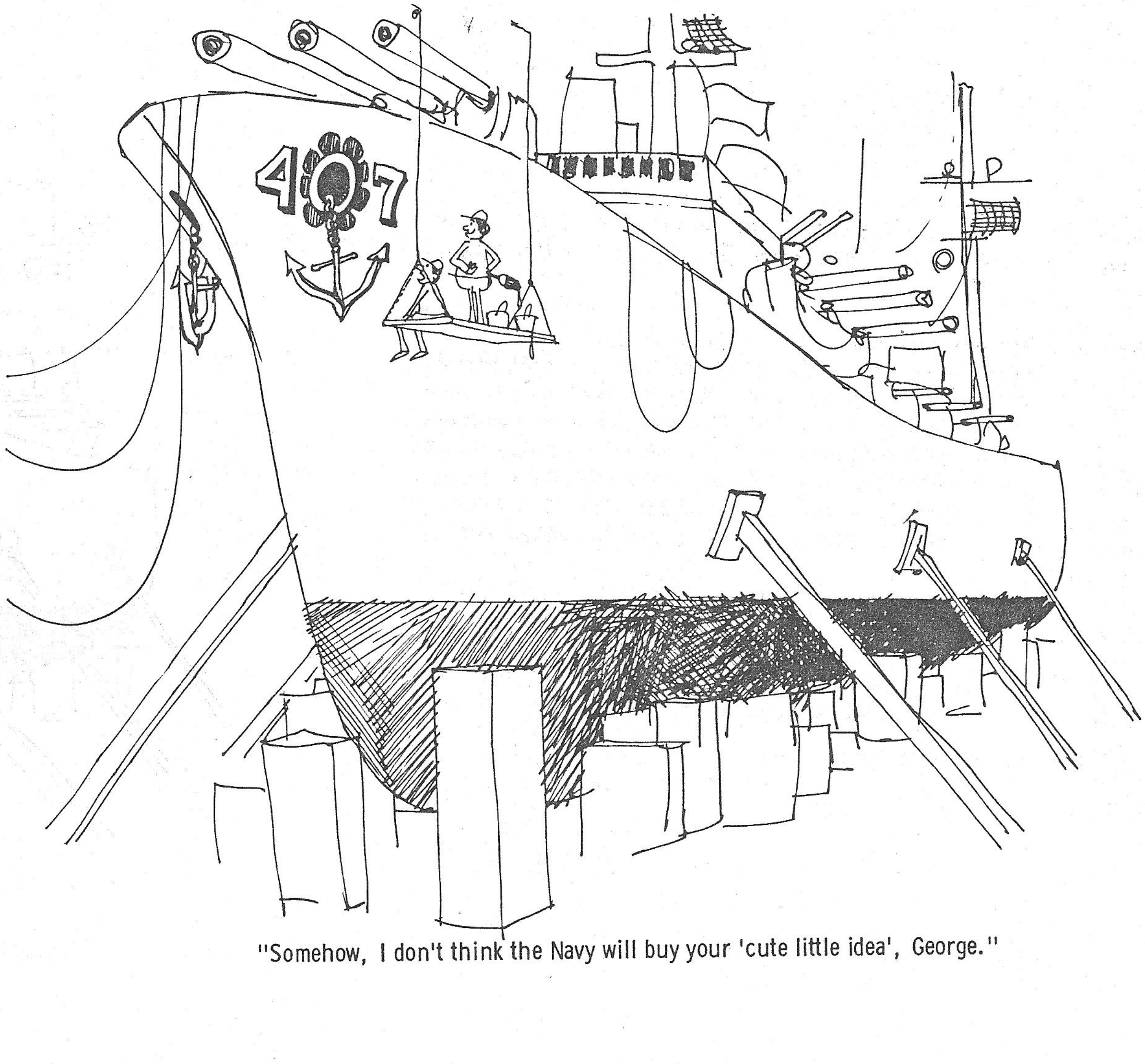

"Somehow, I don't think the Navy will buy your 'cute little idea', George."