PRELIMINARY PROPELLER SELECTION USING THE WAGENINGEN 8-SCREW SERIES AND A GENERAL PURPOSE NON-LINEAR OPTIMIZER (U) NAVAL POSTGRADUATE SCHOOL MONTEREY CA
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Preliminary Propeller Selection Using the Wageningen B-Screw Series and a General Purpose Non-Linear Optimizer

by

Michael Peter Smith II

June 1983

Thesis Advisors: D. Salinas
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(20. ABSTRACT Continued)

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1) diameter limitation
2) cavitation limit on expanded area ratio using Keller's criterion
3) strength requirement determined by an empirical relation and by a method developed by Schoenherr with modifications by the author.

Objective functions considered are maximized open water efficiency and minimized propeller blade weight. Optimized solutions to specific problems previously presented by other authors are obtained and results are compared.
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ABSTRACT

This thesis presents the use of a general purpose non-linear optimization program in the preliminary stage of ship design for the selection of a propeller based on methodical series propeller test data. The propeller series utilized is the well-known Wageningen B-Series. Three (3) "Design Cases", representing the thrust, power and matching approaches to powering problems, are formulated as FORTRAN subprogram analysis codes for solution by the synthesis/optimization program COPES/CONMIN. Designer constraints considered are:

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It has been said:
If someone says it's impossible, then, quite obviously, he has never done it.

With these words in mind, I now recall and give thanks to those who have assisted me in attaining the educational goal represented by this thesis:

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I. INTRODUCTION

A. BACKGROUND

The ship design process, in its most rudimentary form, has been formulated and tracked by the utilization of the classical design spiral (see Figure 1.1). The design follows a convergent helical path past each major milestone "spoke" until, after numerous iterative cycles, the final configuration is "centered" upon. Whether one attempts to segregate the principal phases of Preliminary, Advanced and Contract Design into separate spirals or combine these phases in series along the entire path to the center, it is not long before the designer's roughed-out sketches give way to serious "number crunching", specifically that of propulsion power estimation.

To estimate the power required to drive the ship through the water at its design speed, a decision must first be made as to what type of propulsor (i.e., propeller, water jet, paddle wheel, etc.) will be used. For the average case, and for the discussion that follows, the marine propeller is chosen to be the propulsion device. Since

a ship propeller may be regarded as a transducer that converts the rotational power transmitted through the shaft into the translational power to propel the ship, [Ref. 18: p. 10] the selection and design of this device is obviously an important factor in the eventual size (weight and power) of the ship's propulsion plant. While hydrodynamicists provide
Figure 1.1 Traditional Design Spiral
a myriad of theories and techniques to generate a "custom built" (i.e., wake adapted) propeller for the ship under consideration, their expertise is usually not required in the early stages of preliminary design simply because the design has not been refined enough beyond gross estimates. At this stage, the designer strives to formulate what is possible based on previous experience. For preliminary power estimation, previous propeller designs (i.e., "stock" propellers) and results from methodical series of model propellers are analyzed by the designer in order to select the "best" available propeller under various conditions posed by the problem under consideration. Three examples of typical problems encountered in preliminary ship design are:

1) Given the ship's effective horsepower at a specific speed and estimates of hull performance parameters, which propeller, as determined by certain principal characteristics, will require the least amount of delivered power from the propulsion plant?

2) Given the delivered power from a specific propulsion system in terms of torque and revolution rate at the propeller/shaft interface and estimates of hull performance parameters, which propeller will generate the largest effective horsepower and speed parameters?

3) Given a ship's effective horsepower and speed, various hull performance parameters, and the propulsion plant's delivered power characteristics, which propeller will "match"
these requirements at a minimum amount of weight for a specified material?

(Author's Note: For the sake of brevity, the three selection problems just cited will, henceforth, be referred to as "Design Case No. 1", "Design Case No. 2" and "Design Case No. 3", respectively.)

For this study, the methodical propeller series method is viewed as the designer's choice for preliminary powering analysis. One of the most-widely used methodical series data on model propellers is the Wageningen B-Screw Series. Initially, the results of the series were presented as tabulations of non-dimensional thrust and torque coefficients ($K_T$ and $K_Q$ respectively) versus the non-dimensional advance ratio ($J$) for analytical work and as the familiar "Bp-δ" and "Bu-δ" diagrams for design purposes. As "trial & error" design methods performed by hand in all engineering disciplines gradually transcended to numerical manipulation by the modern digital computer, the necessity for the adaption of the Series results to a format suitable for use in computer-aided design methods became obvious. This was accomplished through multiple regression analysis of the original open-water test data of the 120 propeller models in the Series and presented in the form of polynomial expressions for $K_T$ and $K_Q$ [Refs. 1,2].

The adaptation of the Wageningen B-Screw Series polynomials to various types of propeller selection problems formulated...
for computer solution has been implemented recently by two authors. Triantafyllou [Ref. 3] and, of late, Markussen [Ref. 4] presented different propeller selection problems and proposed different schemes for computer-aided "optimized" solutions. In short, specific expressions for the constraints imposed and the objective (optimality condition) to be maximized, expressed in terms of a number of design variables and parameters, were developed. Then, each system of equations was solved by a Newton-Raphson method to give a solution set of the design variables which maximized the objective and met all constraints.

Rather than formulating and coding a different optimization scheme each time a propeller selection problem presents a different combination and number of design parameters, variables and constraints, a better approach would involve formulating the problem (constraints and objective function) once in terms of all design parameters and variables and utilizing a general purpose optimization scheme which can handle any combination and number of constraints and design variables. This alternative certainly allows the designer more flexibility in solving his problem. Moreover, it eliminates repetitive coding and debugging associated with the implementation of a computer-aided solution for each particular design problem.
B. PROBLEM STATEMENT

The problem, then, is that the previously cited computer-aided "optimized" solutions to the propeller selection problem are not broad enough in capability to handle variations in the problem formulation. The objective of this thesis is to apply an available general purpose optimization computer code to the solution of various propeller selection problems encountered in Preliminary Ship Design in order to enhance the flexibility of the selection procedure.

C. SCOPE

To achieve the stated objective, the general purpose non-linear optimization code CONMIN [Refs. 5,6] together with the engineering synthesis code COPES [Ref. 7] (hereafter referred to collectively as COPES/CONMIN) is utilized in the solution of the three previously cited preliminary design propeller selection problems. Using the Wageningen B-Screw Series propeller characteristics expressed in polynomial expressions of various design variables, three "analysis" codes, required by COPES/CONMIN, are developed in such a way that various combinations of design variables and constraints are used, thereby demonstrating the applicability of the COPES/CONMIN optimization program in the solution of propeller selection problems.

D. THESIS ORGANIZATION

The remainder of the thesis is organized in the following manner.
Chapter II presents a short description of the optimization problem in general terms and a follow-on discussion of the COPES/CONMIN optimization program and the mathematical techniques employed therein.

Chapter III introduces definitions and concepts applicable to the propeller selection problem. A subsequent discussion on the Wageningen B-Screw Series is followed by final comments on constraints imposed on the propeller selection problem.

Chapter IV presents the formulation of the propeller selection problem as a design optimization problem which can be solved using COPES/CONMIN.

Chapter V discusses the background, formulation and programming utilized in estimating a propeller blade's weight for subsequent consideration as an objective function.

Chapter VI reviews the author's modifications to the propeller strength analysis developed by Schoenherr [Ref. 8] in the early 1960's for the American Bureau of Shipping. A subsequent discussion on the programming details of FORTRAN codes, which are utilized for the determination of adequate propeller blade strength, completes the chapter.

Chapter VII reviews the formulation and programming for the analysis code which is used in solving propeller selection problems represented by Design Case No. 1. Sample solutions are presented and compared to those presented previously by other authors.
Chapters VIII and IX consider Design Case No. 2 and Design Case No. 3 selection problems, respectively, in a similar fashion to Chapter VII.

Chapter X, the final chapter, presents the author's conclusions and recommendations.

As a final note, all computer coding presented in this thesis is done in FORTRAN IV, the language used by COPES/CONMIN. For the reader's convenience, Appendix A provides a cross-reference of the symbols presented throughout the thesis to appropriate FORTRAN variable names appearing in the author's codes.
II. OPTIMIZATION

A. INTRODUCTION

The purpose of this chapter is to introduce definitions and concepts used in the formulation and solution of the general optimization problem. Then, a short discussion on the theory and implementation details of COPES/CONMIN is presented.

For further study on the theory and methods of optimization, the reader is directed to the texts by Fox [Ref. 9], Fiacco and McCormick [Ref. 10], and Himmelblau [Ref. 11].

B. DEFINITIONS

Before discussing the techniques of optimization and their application to engineering problems, some preliminary definitions of basic terminology should be stated. Terms which have relevant significance are:

1) Parameters--The numerical quantities for which values are assigned to produce a design are called parameters. From this, it follows that a design may be specified by a vector \( \bar{D} \) containing \( p \) components, each of which is associated with a parameter. That is:

\[
\bar{D} = \begin{pmatrix}
P_1 \\
. \\
. \\
P_p \\
\end{pmatrix}
\]  

(2.1)
However, in a design process, the parameters are determined by some logical procedure through analysis of some kind. Some might take on fixed values to become "preassigned" parameters. Interrelationships among other parameters might exist so that only some of the parameters are changed when one design is compared to another. This consequence leads to the definition of "design variable".

2) Design Variables--The parameters for which values are chosen in some fashion to produce a design are called design variables. They represent an ordered collection of components which is a subset of the design vector $\mathbf{D}$. This subset is unique in that its components are "variable", i.e., they may take on different values in the design process. Having "preassigned" or fixed some of the design's parameters and only allowing the remaining "design variables" to change, leads to the conclusion that a design is now uniquely specified by a vector $\overline{X}$ containing "n" components ($n \leq p$), each of which is associated with a design variable. That is:

$$\overline{X} = \begin{bmatrix} x_1 \\ \vdots \\ x_n \end{bmatrix}$$  \hspace{1cm} (2.2)

3) Objective Function--The computable function of all or some of the design's preassigned parameters and/or design variables, with respect to which the design is to be optimized, is called the objective function. Single valued in
quantitative terms, the objective function's minimum or maximum value represents the "best" obtainable or "optimized" design. It is expressed as $F(\bar{D})$ to show its dependence on the design's parameters. But, since a design can be uniquely defined by $\bar{X}$ alone, then clearly $F(\bar{X})$ suffices as an expression for the objective function.

4) Constraints--Restrictions on the design which must be satisfied in order to produce an acceptable design are called constraints. A constraint may be classified as a "side" or a "behavior" constraint. A side constraint restricts or bounds the range of the design for reasons other than direct consideration of performance. The side constraint on the "i"th design variable may be expressed as:

$$X_{i_{\text{lower}}} \leq X_i \leq X_{i_{\text{upper}}} \quad i = 1, \ldots, n \quad (2.3)$$

A constraint derived from those performance or behavior requirements that are explicitly considered is called a behavior constraint. Most often, it appears as a computable functional relation involving the design's parameters, both preassigned and variable alike. The relation may be an inequality so that the "j"th of "m" inequality constraints can be expressed as:

$$G_j(D) \leq 0 \quad j = 1, \ldots, m \quad (2.4)$$
Alternatively, the relation may be an equality on the "k"th of "n" equality constraints expressed as:

\[ H_k(D) = 0 \quad k = 1, \ldots, \lambda \]  

(2.5)

Of noteworthy importance here is that, as before, if some of the design's parameters are preassigned, then the resulting design is that defined by \( \bar{X} \) which contains only the parameters that can be varied in the design process, i.e., the design variables. Therefore, constraints imposed upon the design may be expressed under one equation as:

\[ G_j(\bar{X}) \leq 0 \quad j = 1, \ldots, m \]
\[ H_k(\bar{X}) = 0 \quad k = 1, \ldots, \lambda \]  

(2.6)

\[ x_{i,\text{lower}} \leq x_i \leq x_{i,\text{upper}} \quad i = 1, \ldots, n \]

A final form for constraints is that of the discrete-valued design variable.

5) Feasible Design--A design in which specified constraints are satisfied is called a feasible or "acceptable" design.

6) Infeasible Design--A design in which constraints are violated is called an infeasible or "unacceptable" design.

C. PROBLEM STATEMENT

If one presupposes that a range of designs exists within a selected design concept, then it follows that different
methodologies also exist by which one may choose the parameters which describe the design. One such method is optimization where parameters are chosen in a way that the design will satisfy all of the limitations and restrictions imposed upon it and will be "best" in some sense. In view of the foregoing definitions, optimization is then a selection method applied to a design problem by which an objective function $F(\bar{D})$ is minimized to produce an acceptable design which satisfies a certain set of requirements called constraints.

Formulated mathematically, the general, non-linear, constrained optimization problem may be stated under one equation as:

Minimize: \[ F(\bar{D}) = \text{OBJ} \]
Subject to: \[ G_j(\bar{D}) \leq 0 \quad j = 1, \ldots, m \quad (2.7) \]
\[ H_k(\bar{D}) \leq 0 \quad k = 1, \ldots, l \]
\[ x_{l_{\text{lower}}} \leq x_i \leq x_{l_{\text{upper}}} \quad i = 1, \ldots, n \]

Again, as pointed out in the previous section, the design may be uniquely defined by just its design variables as specified by $\bar{X}$ when some parameters are preassigned. Thus, the general, non-linear, constrained optimization problem can now be stated under one equation as:
Minimize: \[ F(\mathbf{x}) = \text{OBJ} \]

Subject to: \[ G(\mathbf{x}) \leq 0 \quad j = 1, \ldots, m \quad (2.8) \]
\[ H_k(\mathbf{x}) = 0 \quad k = 1, \ldots, \ell \]
\[ x_{i}^{\text{lower}} \leq x_i \leq x_{i}^{\text{upper}} \quad i = 1, \ldots, n \]

Solutions methods for this optimization problem are abundant. Those pertaining to the linear and quadratic optimization problems involving a few design variables are most often presented in graphical or analytic form, although numerical schemes are, by no means, a dormant form. Structural and thermal problem solutions are most prevalent. However, as the optimization problem becomes more complex in terms of non-linear relationships among an increasing number of design variables and of an increased number of design constraints, numerical or mathematical programming techniques dominate the solution methods.

To limit the scope of this discussion, only the numerical techniques relevant to COPES/CONMIN will be considered. For more background on optimization techniques and applications, the reader is directed to a recent paper by Vanderplaats [Ref. 12] which presents a concise, but thorough, qualitative review of optimization. Although this paper deals exclusively with the application of design optimization to structural problems, it also contains a very extensive and current list of references on general techniques and applications of optimization.
D. COPES/CONMIN

As previously stated in Chapter I, COPES/CONMIN is the collective acronym for the FORTRAN program utilizing the optimization code CONMIN and the synthesis code COPES. COPES stands for Control Program for Engineering Synthesis; CONMIN is an acronym for CONstrained function MINimization.

1. CONMIN

CONMIN is a FORTRAN program, in subroutine form, which solves the general non-linear constrained optimization problem as stated:

Minimize: \( F(\bar{X}) = \text{OBJ} \)

Subject to: \( G_j(\bar{X}) \leq 0 \) \( j = 1, \ldots, m \) \( (2.9) \)

\[ x_i^{\text{lower}} \leq x_i \leq x_i^{\text{upper}} \] \( i = 1, \ldots, n \)

Equation (2.9) applies to the entire statement. Observe that equation (2.9) differs from equation (2.8) in that the equality constraint set, given by \( G_\bar{X}(\bar{X}) = 0 \), is not specified. This is because the version of COPES/CONMIN used in this study does not consider these types of constraints. However, this will not pose any difficulty in solving the propeller selection problems previously cited.

Again, \( F(\bar{X}) \) is the objective function (OBJ). The vector \( \bar{X} \) contains the "n" design variables (NDV). \( G_j(\bar{X}) \) are the "m" inequality behavior constraints (NCON) imposed on the optimization problem; \( x_i^{\text{lower}} \) and \( x_i^{\text{upper}} \) are the
respective lower and upper side constraints which bound the "design space" over which $F(\bar{x})$ and $G_j(\bar{x})$ are defined. As functional relationships involving $\bar{x}$, $F(\bar{x})$ and $G_j(\bar{x})$ may be implicit or explicit, but, in any event, must be continuous and have finite numerical values.

When the inequality condition of equation (2.9) is not satisfied, i.e., $G_j(\bar{x}) > 0$ for any constraint, the constraint is said to be violated. If the equality condition is met, i.e., $G_j(\bar{x}) = 0$ for any constraint, the constraint is said to be active. And, finally, if the inequality condition is satisfied, i.e., $G_j(\bar{x}) < 0$, for any constraint, that constraint is termed inactive. Any design, defined by $\bar{x}$, which satisfies the inequalities of equation (2.9) is designated as a feasible design. Likewise, any one which violates these inequalities is termed an infeasible design. The feasible design with the minimum objective function value, often referred to as the "minimum feasible design", will, therefore, be the optimum design.

During the optimization process, CONMIN employs the Fletcher-Reeves algorithm [Ref. 13] for locally unconstrained problems, and Zoutendijk's method of feasible directions [Refs. 14,15] for locally constrained problems, in a numerical procedure which attempts to minimize the objective function, $F(\bar{x}) = OBJ$, until one or more of the constraints, $G_j(\bar{x})$, becomes active. The numerical search procedure begins with an initial $\bar{x}$ vector which may or may not specify a feasible
design. Modifications are included in CONMIN so that, if the initial design is infeasible, a feasible solution will be obtained with minimal increase in $F(\bar{x})$. By iteratively updating the design vector $\bar{x}$ by the following relation:

$$\bar{x}(q+1) = \bar{x}(q) + \alpha^* s(q)$$

(2.10)

the optimization process continues by following the constraint boundaries in a direction of search $s$ so that the value of $F(\bar{x})$ decreases with each iteration $q$. The scalar $\alpha^*$ defines the distance of travel in the direction of search $s$. The process terminates when a vector $\bar{x}$ is found such that no further decrease in $F(\bar{x})$ can be made. The vector $\bar{x}$ is considered to be optimal and, at least, a local minimum.

CONMIN can be used alone as a subroutine in any FORTRAN program where numerical optimization is desired. However, in order to make the optimization process more "user-friendly", CONMIN has been coupled to COPES in order to simplify its application to various types of problems. Further information on CONMIN can be found in previously cited references [5] and [6].

2. COPES

COPES is a FORTRAN program that provides automated design and trade-off capability to the design engineer. It utilizes the optimizer CONMIN to provide the following six specific capabilities:
1) simple analysis
2) optimization
3) sensitivity analysis
4) two variable function space analysis
5) optimum sensitivity
6) optimization using approximation techniques

During the execution of COPES, say for optimization, three principal tasks are performed:

1) data management on the design variables and constraints through location assignments in a FORTRAN common block called GLOBCM.

2) decision process control on the attainment of an optimal design vector $\bar{X}$ through multiple calls to the optimizer until a minimum or maximum value of OBJ is achieved and all $G_j(\bar{X})$ are satisfied.

3) evaluation of OBJ and $G_j(\bar{X})$ at each $\bar{X}^q$ and $\bar{X}^{q+1}$ when ICALC = 2 through multiple calls to the user-provided analysis subprogram, SUBROUTINE ANALIZ.

For the application under consideration in this study, only the optimization capability will be used. Therefore, further elaboration on the other capabilities is not warranted.

Reference [7] is the user's manual for COPES/CONMIN. Details on the mechanics of user implementation are presented with subsequent illustration by example. The reader is, therefore, encouraged to familiarize himself with the reference. However, at this point, it is sufficient to be aware of the fact that a user of COPES/CONMIN is required to:
1) provide a FORTRAN subroutine called ANALIZ which performs the input of preassigned parameters, the evaluation of the objective function and constraints during the analysis phase of the optimization search and the output of the results.

2) provide an assembled deck of control cards required by COPES.

E. CONCLUDING NOTE

The field of optimization is both extensive and complex and, therefore, the foregoing presentation is, by no means, complete in every detail. However, it is felt that the preceding overview, in conjunction with the cited references, covers the necessary prerequisites that will enable the reader to follow the application of COPES/CONMIN to the various propeller selection problems in the chapters that follow.
III. POWERING, PERFORMANCE AND PROPELLERS

A. INTRODUCTION

The purpose of this chapter is to present an overview of the terminology and concepts that pertain to ship propulsion, propeller selection and the use of model propeller test data. Initially, fundamental definitions used in ship powering problems are presented. This is followed by a discussion of the "classic" types of propeller design/selection problems encountered by the naval architect and marine and naval engineers. Propeller model testing and propeller performance characteristics are reviewed next. The chapter is completed with a discussion of the Wageningen B-Screw Series.

The goal here is brevity. The reader is, therefore, encouraged to investigate the references cited for further details.

B. DEFINITIONS

Some fundamental terms associated with most propeller design/selection problems are:

1) Effective Horsepower \((P_E)\)--power required to tow the "bare" hull (without propeller; rudder and appendage allowance assumed included) that generates a given resistance \((R_T)\) at a given speed \((V)\). It is determined by:

\[
P_E = \frac{R_T V}{550}
\]  

(3.1)
2) Thrust Horsepower ($P_T$)--power delivered to water by a propeller developing a thrust force ($T$) and moving at a speed of advance ($V_A$) without the influence of a hull form ahead of it. $P_T$ is determined by:

$$ P_T = \frac{T \cdot V_A}{550} \quad (3.2) $$

3) Delivered Horsepower ($P_D$)--power delivered by shaft to propeller, normally specified at the outboard side of the stern tube. $Q_S$ is the torque delivered to the propeller; $n_P$ is the revolution rate of the shaft and, consequently, the propeller. $P_D$ is determined by:

$$ P_D = \frac{2\pi \cdot Q_S \cdot n_P}{550} \quad (3.3) $$

4) Shaft Horsepower ($P_S$)--power delivered to the inboard side of the stern tube having a transmission efficiency of $\eta_S$. $P_S$ is determined by:

$$ P_S = \frac{P_D}{\eta_S} \quad (3.4) $$

5) Brake Horsepower ($P_B$)--power delivered by the prime mover at connection flange to the power train. While $P_B$ is normally associated with the prime mover's rated power at this connection (BHP), it can also be specified from the power train/propeller side as:
\[ P_B = \frac{P_S}{\eta_B \eta_G} \quad (3.5) \]

where \( \eta_B \) and \( \eta_G \) are, respectively, the bearing system and reduction gear transmission efficiencies.

6) Thrust deduction factor (1-td)--ratio of the tow resistance \( (R_T) \) to the thrust \( (T) \) provided by the propeller. It is determined by

\[ (1-\text{td}) = \frac{R_T}{T} \quad (3.6) \]

7) Wake Factor (Taylor's) (1-wt)--ratio of the speed of advance \( (V_A) \) to the ship's speed \( (V) \). It is given by:

\[ (1-\text{wt}) = \frac{V_A}{V} \quad (3.7) \]

8) Advance Ratio \( (J) \)--a non-dimensional value, associated with propeller test data presentation (see figure (3.1)), given by the following relation:

\[ J = \frac{V(1-\text{wt})}{n_p D} = \frac{V_A}{n_p D} \quad (3.8) \]

9) Thrust Coefficient \( (K_T) \)--a non-dimensional value associated with the thrust force \( (T) \) developed by a propeller of diameter \( D \) which is turning at a rate \( n_p \) and operating in a fluid of density \( \rho \). It is defined by the following expression:
\[ K_T = \frac{T}{\rho n_p^2 D^4} \quad (3.9) \]

10) Torque Coefficient \((K_Q)\)--a non-dimensional value associated with the torque \((Q_p)\) absorbed by a propeller of diameter \(D\) which is turning at a rate \(n_p\) and operating in a fluid of density \(\rho\). It is defined by the following expression:

\[ K_Q = \frac{Q_p}{\rho n_p^2 D^5} \quad (3.10) \]

11) Open Water Efficiency \((\eta_o)\)--the ratio of \(P_T\) to \(P_D\) for a propeller in open water conditions, with a uniform inflow velocity field at a speed of advance \(V_A\). It is expressed as:

\[ \eta_o = \frac{P_T}{P_D} = \frac{T V_A}{2\pi n_p Q_S} = \frac{J K_T}{2\pi K_Q} \quad (3.11) \]

12) Hull Efficiency \((\eta_H)\)--a ratio of work done on the ship to that done by the propeller expressed as:

\[ \eta_H = \frac{P_E}{P_T} = \frac{R_T V}{T V_A} = \frac{(1-td)}{(1-wt)} \quad (3.12) \]

13) Relative Rotative Efficiency \((\eta_R)\)--the ratio of the actual, behind-hull efficiency to the open water efficiency. The value of \(\eta_R\) does not, in general, depart from the value
of 1.0. Most often, $\eta_R$ varies between 0.95 and 1.0 for twin-screw ships and between 1.0 and 1.1 for single screw ships.

Applicable units for the terms in the expressions above are:

1) horsepower (hp) -- $P_E$, $P_T$, $P_S$, $P_D$ and $P_B$
2) pounds (lbf) -- $R_T$, $T$
3) feet/second (ft/sec) -- $V$, $V_A$
4) foot-pounds (ft-lbf) -- $Q_S$, $Q_P$
5) feet (ft) -- $D$
6) revolutions/second (rps) -- $n_p$
7) revolutions/minute (rpm) -- $N_p = n_p/60.0$

The quantities $T$, $V_A$, $D$, $Q_p$ and $n_p$ are obtained from the propeller test data results. The quantities $R_T$ and $V$ are specified from the design point on the $R$-$V$ curve for the hull under study. The quantity $\rho$ is a property of the fluid in which the hull and propeller operate. And, finally, $\eta_B$, $\eta_G$ and $\eta_S$ are characteristics of the bearing, gear and stern tube systems. In preliminary design studies, nominal values, based on previous designs, are usually assumed unless, of course, these systems have been selected and actual values can be specified.

C. POWERING CONCEPTS

1. Basic Relations

Simply stated, the fundamental powering relationship to be solved in ship propulsion and powering problems is:
\[ P_E = \frac{(1-td)}{(1-wt)} \cdot \eta_R \eta_o P_D \]  \hspace{1cm} (3.13)

Utilizing the definitions just presented, equation (3.13) can be rewritten as:

\[ \frac{R_T V}{550} = \frac{(1-td)}{(1-wt)} \cdot \eta_R \eta_o \cdot \frac{2\pi Q_S n_p}{550} \]  \hspace{1cm} (3.14)

Rearranging terms of equation (3.14) gives:

\[ \frac{R_T (1-wt)V}{(1-td)} = \eta_R \eta_o \cdot \frac{2\pi Q_S n_p}{550} \]  \hspace{1cm} (3.15)

And, finally, when substitutions are made, equation (3.15) becomes:

\[ \frac{T V_A}{550} = \frac{T(1-wt)V}{550} = \eta_R \eta_o \cdot \frac{2\pi Q_S n_p}{550} \]  \hspace{1cm} (3.16)

Equations (3.14), (3.15), and (3.16) provide the basis for different approaches to the solution of a typical powering problem. More background and information on the definitions and equations presented above may be found in Chapter VI, Sections 10-16 in the text by Comstock [Ref. 16] and O'Brien's book [Ref. 17].

2. **Approaches to the Powering Problem**

From equation (3.16), three types of propeller selection problems are discernible. In the first instance, the propeller thrust \( T \) and the propeller's speed of advance \( V_A \)
are taken as known quantities. The fact that T is known substantiates the "Thrust Approach" nomenclature given to this type of selection problem. In the preliminary (or, in some circles, conceptual) ship design phase, the specification of T is based upon the requirement imposed by the resistance of the ship (R_T) at its design speed (V) (or, the effective horsepower (P_E) at V) and estimates of wt and td in the absence of wake surveys and self-propulsion data from model tests. Essentially, the thrust delivered by a selected propeller must provide, at least, the thrust required for the ship hull under study. The objective in the "Thrust Approach" selection problem is to determine, by logical means, the appropriate values of Q_S and n_P when the open water efficiency (\eta_o) is set by the selected propeller and its performance characteristics.

In the second instance, the delivered torque (Q_S) and the propeller shaft speed (n_P) are taken to be known. The "Power Approach" nomenclature is given to propeller selection problems of this type because P_D is known. Here, with the shaft and propeller speeds being equal, the torque absorbed by the propeller (Q_P) must be, at least, equivalent to the delivered torque (Q_S). The corresponding objective in the "Power Approach" selection problem is to determine, by logical means, the expected ship speed (V) (or, the speed of advance (V_A)) and the associated thrust (T) that can be developed when the open water efficiency (\eta_o) is, again, set by the selected propeller and its performance characteristics.
The final, and most familiar, types of propeller selection problem occurs when \( T, V_A \) or \( V, Q_s \) and \( n_p \) are all known. From equation (3.16), the open water efficiency \( (n_0) \) is now established as a requirement to be met. The objective is, simply, to select a propeller whose open water efficiency \( (n_0) \), developed thrust and absorbed torque are equivalent to or "match" the requirements imposed. Obviously, this approach on the selection problem has been designated as a "matching problem".

The reader is directed to the paper by Vassilopoulos [Ref. 18] for further information.

D. PROPELLER PERFORMANCE CHARACTERISTICS

Up until the late 1950's, much of the knowledge about the performance of propellers has been gained from experience with models. To study the relationships governing their behavior, a model propeller is built and run in a towing tank without any hull ahead of it. This is done by running the propeller on a long shaft projecting well ahead of a narrow, hydrodynamically shaped pod or "propeller boat" which contains the driving mechanism and recording apparatus and is attached to the towing carriage. The propeller advances into undisturbed fluid (usually water of density \( \rho \) and kinematic viscosity \( \nu \)) so that the speed of advance \( (V_A) \) is known and the flow into the "disc" swept by the turning blades is uniform. For the model propeller of diameter \( (D) \) under test, readings of thrust \( (T) \), torque \( (Q_s) \) and shaft revolutions \( (n_p) \)
are recorded over a range of values for speed of advance \( (V_A) \) in this "open water" condition.

Using the laws of similitude, the collected data is reduced and scaled appropriately into the familiar functional relationships between the advance ratio \( (J) \) and the non-dimensional coefficients of propeller performance. These coefficients or performance characteristics, defined previously, are:

1) Thrust Coefficient \( (K_T) \)
2) Torque Coefficient \( (K_Q) \)
3) Open Water Efficiency \( (\eta_0) \)

Figure (3.1) graphically depicts the relationship between \( J \) and \( K_T \) and \( K_Q \) derived from test data for a propeller defined by a specific expanded area ratio \( (A_E/A_0) \), pitch-diameter ratio \( (P/D) \), number of blades \( (Z) \) and thickness-to-chord ratio \( (t/c) \).

Definitions of these terms with graphical illustrations pertaining to various aspects of propeller geometry can be found in Section 15 of references [16], [17] and in van Manen's publication [Ref. 19].

More recently, highly analytical theories (lifting line, modified lifting line, lifting surface, etc.) for use with high-speed digital computers have been formulated and subsequently used in "modeling", in a mathematical sense, the propeller and its behavior in the "wake adapted" (or, behind hull) condition as well as the "open water" condition.
Figure 3.1  Open Water Test Results—B 4-100 Series Propeller
Additional benefits derived from this approach to propeller performance analysis include:

1) determination of blade section profiles along the propeller's blade radius (R) to achieve uniform lift and internal stress distributions;

2) computation of "off-design" performance characteristics in all quadrants;

3) subsequent determination of hull surface forces, bearing loads and spindle torques induced by the propeller;

4) prediction of steady and unsteady stress distributions in the propeller blade using the finite element method on the blade of the propeller under study.

Obviously, this approach to propeller performance analysis serves to:

1) eliminate the time-consuming and expensive model construction and testing of propellers in tow tanks and cavitation tunnels;

2) eliminate the "scaling" discrepancies which inhibit the reliability of design charts and model propeller data;

3) eliminate those design charts altogether.

As in the case with model experiments, however, the ultimate objective remains the same, i.e., establishing the performance characteristics of the propeller in terms of $K_T$, $K_Q$ and as functions of $J$. Having these relationships enables the ship designer to proceed in solving the power equation (equation (3.13)) through any of the approaches previously discussed.
E. THE WAGENINGEN B-SCREW SERIES

1. Background

The model test data of the Wageningen B-Screw Series have been selected for use in the powering problems to be solved utilizing COPES/CONMIN. The choice was driven by the following considerations:

1) the Series is widely known and, despite its growing obsolescence, is still used in preliminary ship design studies.

2) the availability of previous investigations [Refs. 3,4] which utilized the series, for comparative analysis of optimization results.

3) the applicability of the polynomial expressions for $K_T$ and $K_Q$ to computer-aided analysis.

The Series tests were conducted from 1940 through 1960 and, therefore, represent propeller designs (principally naval and merchant applications) and design philosophy of that era.

Specifically, the Series consists of 120 model propellers. As is customary in methodical or systematic model propeller series testing, the number of blades ($Z$), expanded area ratio ($A_E/A_O$) and pitch-diameter ratio ($P/D$) are varied systematically, while the blade outline, the profile of the blade's cross section along the blade radius, blade cross section maximum thickness ($t$), blade section chord length ($c$), diameter ($D$) and propeller hub-to-diameter ratio ($d/D$) were kept constant for given values of $A_E/A_O$ and $Z$. 
Table (I) summarizes the variations in $Z$ and $A_E/A_O$ for each set of model propellers having pitch-diameter ratios (P/D) of 0.4, 0.6, 0.8, 1.0, 1.2 and 1.4.

TABLE I
Summary of the Wageningen B-Screw Series

<table>
<thead>
<tr>
<th>Blade number</th>
<th>$Z$</th>
<th>Blade area ratio</th>
<th>$A_E/A_O$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>0.30</td>
<td>0.35</td>
<td>0.40</td>
</tr>
<tr>
<td>3</td>
<td>0.50</td>
<td>0.50</td>
<td>0.65</td>
</tr>
<tr>
<td>4</td>
<td>0.45</td>
<td>0.55</td>
<td>0.60</td>
</tr>
<tr>
<td>5</td>
<td>0.50</td>
<td>0.60</td>
<td>0.70</td>
</tr>
<tr>
<td>6</td>
<td>0.55</td>
<td>0.65</td>
<td>0.75</td>
</tr>
<tr>
<td>7</td>
<td>0.70</td>
<td>0.80</td>
<td>0.85</td>
</tr>
</tbody>
</table>

2. Series Results

The test results of the Wageningen B-Screw Series were originally presented in the form of $Bp-\delta$, $Bu-\delta$ and $K_T$, $K_Q$, and $J$ diagrams. As stated in Chapter I, multiple regression analysis was performed (again, [Refs. 1,2]) on the results to produce the polynomial expressions for $K_T$ and $K_Q$. The open water efficiency ($\eta_0$), as a function of $J$, follows from equation (3.11). The correction for "scale effects" was achieved by using Lerb’s method of equivalent profiles [Ref. 20]. Although Triantafyllou's thesis [Ref. 21] suggests an improved method for scale correction, the results of Reference [2] will be used in this study.

45
In propeller selection problems which use this Series, values for \( K_T \) and \( K_Q \) are defined as:

\[
K_T = f_1(J,P/D,A_E/A_Q,Z,t*/c.75R) \tag{3.17}
\]

\[
K_Q = f_2(J,P/D,A_E/A_Q,Z,t*/c.75R) \tag{3.17}
\]

To compute \( K_T \) and \( K_Q \), the following equations are used:

\[
K_T = K_T' + \Delta K_T 
\]

\[
K_Q = K_Q' + \Delta K_Q 
\]

The polynomial expressions found in Tables (5) and (6) of Reference [2] are then used to evaluate to components \( K_T' \), \( K_Q' \), \( \Delta K_T \) and \( \Delta K_Q \).

Table (5) in Reference [2] lists the coefficients used in the polynomial expressions for \( K_T' \) and \( K_Q' \) at an equivalent Reynolds number (\( Rn .75R \)) of \( 2 \times 10^6 \). It is defined as:

\[
Rn .75R = \frac{c .75R \sqrt{\left(\frac{V_A}{\nu}\right)^2 + (0.75\pi n_p D^2)}}{\nu} \tag{3.19}
\]

where:

\[
\nu = \text{kinematic viscosity of the fluid (ft}^2/\text{sec)};
\]

\[
c .75R = \text{blade section chord length at 3/4 propeller radius (.75R) in feet (ft)}.
\]
To account for "other effects", coefficients $\Delta K_T$ and $\Delta K_Q$ are introduced. Table (6) in Reference [2] lists the coefficients used in the polynomial expressions for these coefficients. "Other effects" include the operation of the propeller at an equivalent Reynolds Number different from $2 \times 10^6$. Also, variations in other parameters which define the propeller's geometry, specifically t/c values different from the ones fixed by the Wageningen propellers, are taken into account by corrections to the equivalent Reynolds number. By keeping the blade section's chord length (c) at the value of the Wageningen propeller, a change in a blade section's maximum thickness from the standard one defined by the Series (t ) to one preferred in the selection (t* ) produces a new equivalent Reynolds number ($R_{n.75R}^*$) given by:

$$R_{n.75R}^* = \exp \left[ 4.6052 + \left\{ \frac{1+2(t/c)_{75R}}{1+2(t*/c)_{75R}} \ln (R_{n.75R} - 4.6052) \right\} \right]$$

(3.20)

where:

- $R_{n.75R}^*$ = the new equivalent Reynolds number;
- $(t*/c)_{75R}$ = new equivalent t/c at 3/4 propeller radius;
- $R_{n.75R}$ = the Reynolds number computed by equation (3.19);
- $(t/c)_{75R}$ = standard equivalent t/c at 3/4 propeller radius for Wageningen propellers.
For the Wageningen B-Screw Series, the standard equivalent t/c is given by:

\[ t/c_{.75R} = \frac{(0.0185 - 0.00125Z)Z}{2.073 \frac{A_E}{A_O}} \]  

Further details on blade section geometry will be addressed in Chapter V. Reference [2] contains background and other information on the equations above.

3. Limitations on Series Data

In utilizing the Wageningen B-Screw Series in any propeller selection problem, the following restrictions apply to the Series data:

1) Number of Propeller Blades (Z)--The Series considers only propellers with numbers of blades as shown in Table (I). Therefore,

\[ Z = 2, 3, 4, 5, 6 \text{ or } 7 \]  

However, the two bladed propeller, i.e., \( Z = 2 \), is not very common in conventional merchant and naval ship designs and, therefore, is not included in this study.

2) Equivalent Reynolds Number--The Series data, as published, is valid only in the range of equivalent Reynolds numbers given by:

\[ 2 \times 10^6 \leq \text{Rn}_{.75R} \leq 2 \times 10^9 \]
If the equivalent t/c is varied from the standard equivalent value \((t/c)_{.75R}'\), then the new equivalent Reynolds number \((R_{n_{.75R}}^*)\), which results from this variation, must lie within the same limits. That is,

\[2 \times 10^6 \leq R_{n_{.75R}}^* \leq 2 \times 10^9\]  

(3.24)

These limits are appropriate for full-size propellers. For example, given the following:

a) \(w_t = .22\)

b) \(V = 20\) (knots)

c) \(N_p = 104\) (rpms)

d) \(D = 25\) (ft)

e) \(c_{.75R} = 4.0\) (ft)

f) \(v = 1.2285 \times 10^2\) (ft\(^2\)/sec)

the value for \(R_{n_{.75R}}\) is equal to \(3.619 \times 10^7\).

3) Pitch-diameter Ratio (P/D)--The series data considers only pitch diameter ratios in the range given by:

\[0.4 \leq P/D \leq 1.4\]  

(3.25)

4) Advance Ratio (J)--An inspection of the Series results in graphical format shows that J varies over a range given by:

\[0 < J < 1.6\]  

(3.26)
5) Expanded Area Ratio ($A_E/A_o$)--Using Table (I), $A_E/A_o$ varies over certain ranges depending on $Z$. This is stated as:

\[ 0.35 \leq A_E/A_o \leq 0.8 \quad Z = 3 \quad (3.27) \]

\[ 0.40 \leq A_E/A_o \leq 1.0 \quad Z = 4 \quad (3.28) \]

\[ 0.45 \leq A_E/A_o \leq 1.05 \quad Z = 5 \quad (3.29) \]

\[ 0.50 \leq A_E/A_o \leq 0.8 \quad Z = 6 \quad (3.30) \]

\[ 0.55 \leq A_E/A_o \leq 0.85 \quad Z = 7 \quad (3.31) \]

6) Hub diameter-to-Propeller Diameter Ratio ($d/D$)--From Table 37, Section 17 of Reference [16], the Series data requires that:

\[ d/D = 0.18 \quad Z = 3,7 \quad (3.32) \]

\[ d/D = 0.167 \quad Z = 4,5,6 \quad (3.33) \]

F. SUMMARY

From the preceding discussions, the following observations can be made:

1) the "Design Cases", defined in Chapter I, are examples of the powering equation solution approaches. That is, Design
Case No. 1 constitutes a "Thrust Approach" problem; Design Case No. 2, a "Power Approach" one; Design Case No. 3, a "Matching" problem.

2) equations (3.17) and (3.8) imply that an optimization solution to the "Design Cases" will involve $P_E$, $V$, $wt$, $D$, $P/D$, $A_E/A_O$, $(t/c) .75R$, $Q_S$ and $n_p$ as possible design variables.

3) when viewed from the concepts on optimization presented in Chapter II, equations (3.25) through (3.31) constitute side constraints to an optimized solution of a propeller selection problem which uses the Wageningen B-Screw Series. Having noted these points, the propeller selection problem can now be formulated as a general, non-linear, constrained optimization problem.
IV. PROPELLER SELECTION--AN OPTIMIZATION PROBLEM

A. INTRODUCTION

The purpose of this chapter is to present the formulation of the propeller selection problem as an optimization problem that can be solved using COPES/CONMIN. Three usual restrictions considered by the designer in any propeller selection analysis are stated as constraints. Then, the components of $\bar{D}$ and $\bar{X}$ are assembled based on requirements from previously cited relationships. The restrictions considered by the designer and the limitations imposed by the use of the Wageningen B-Screw Series are presented in inequality constraint format. A formal statement of the propeller selection problem as an optimization problem is followed by a review of the GLOBCM common block format and the basic subprograms used in all three versions of SUBROUTINE ANALIZ that pertain to each Design Case.

The FORTRAN subprogram listings are found in Appendix B. Comment cards have been used extensively in the coding development to assist the reader.

B. DESIGNER'S CONSIDERATIONS

1. Propeller Size

The first restriction on the selection of any propeller is size. That is, the propeller race in the stern of the hull under consideration will only accommodate a
propeller of some given maximum diameter ($D_{\text{lim}}$). As a constraint on a selected propeller of diameter $D$, this may be written as:

$$D \leq D_{\text{lim}} \quad (4.1)$$

or, alternatively, as:

$$G_9(\bar{x}) = \frac{D}{D_{\text{lim}}} - 1 \leq 0 \quad (4.2)$$

2. Cavitation

Another item of importance in propeller selection is the cavitation phenomenon. When a propeller of given diameter $D$ and expanded area ratio $A_E/A_0$ is operating to produce a thrust $T$, the formation and subsequent collapse of water vapor bubbles on the blade surface, i.e., cavitation, is likely to occur if the localized surface pressures, usually on the "back" side of the blade, drop below the pressure at which the fluid would boil ($P_{\text{vatvap}}$) in the surrounding environment. Avoidance of cavitation can be reasonably assured by selecting a propeller having certain geometric characteristics. A good empirical relationship that establishes these characteristics for propellers typified by the Wageningen B-Screw Series is the Keller Cavitation criterion [Ref. 2: p. 259]. It specifies the minimum required expanded area ratio ($A_E/A_0_{\text{min}}$) to avoid cavitation and is given by:
\[(A_E/A_O)_{\text{min}} = \frac{(1.3 + 0.3Z)}{(P_{\text{atm}} + \rho \cdot acg \cdot h_{ci} - \rho_{\text{watvap}})} \cdot \frac{T}{D^2} + b\] (4.3)

where:

- \(Z\) = number of blades;
- \(T\) = developed thrust (lbf);
- \(D\) = propeller diameter (ft);
- \(P_{\text{atm}}\) = atmospheric pressure (psia);
- \(P_{\text{watvap}}\) = fluid vaporization pressure (psia);
- \(\rho\) = fluid density (lbf sec\(^2\)/ft\(^4\))
- \(acg\) = 32.174 (ft/sec\(^2\))
- \(h_{ci}\) = depth to shaft centerline (ft)
- \(b\) = constant: 0.1 for \(Z = 2\), 0.2 for \(Z = 1\).

As a constraint on the propeller selection, this requirement is written as:

\[(A_E/A_O)_{\text{min}} \leq A_E/A_O\] (4.4)

or

\[G_{10}(\bar{X}) = \frac{(A_E/A_O)_{\text{min}}}{A_E/A_O} - 1 \leq 0\] (4.5)

3. **Strength**

The final designer's consideration (for this study), included in the selection of a propeller, is that of strength.
Given the propeller's material (promat), selected from Table (II), and the loadings (T and Q_s) imposed, it is important to ensure that the blade's cross sections have proper dimensions (in an ideal sense, maximum blade section thickness (t*) and chord length (c)) to ensure adequate strength. Since the use of the B-Screw Series requires that the chord length (c) vary as a prescribed function of D, Z and A_e/A_o, as given in Table 1 of Reference [2], the adequacy for strength can be determined by an appropriately selected value for blade section maximum thickness-to-chord ratio (t*/c) alone. So, if t*_{min} is the established minimum blade section maximum thickness, then the strength requirement follows from the constraint given by:

\[
\frac{t^{*}_{\text{min}}}{c} = \left(\frac{t^{*}}{c}\right)_{\text{min}} < \frac{t^{*}}{c} \quad (4.6)
\]

The fact that blade section maximum thickness for the B-Screw Series varies linearly with the propeller radius (R) allows the strength constraint (equation (4.6)) to be evaluated at one section along the radius. This point is chosen to be at the 3/4 radius (.75R). Therefore, equation (4.6) becomes:

\[
\left(\frac{t^{*}}{c}\right)_{.75R \text{ min}} < \left(\frac{t^{*}}{c}\right)_{.75R} \quad (4.7)
\]

or

\[
G_{11}(\bar{X}) = \frac{\left(\frac{t^{*}}{c}\right)_{.75R \text{ min}}}{\left(\frac{t^{*}}{c}\right)_{.75}} - 1 < 0 \quad (4.8)
\]
Reference [2] suggests the following empirical relation for the minimum required equivalent blade section maximum thickness-to-chord ratio \((t^*/c)_{\text{75R min}}\):

\[
(t^*/c)_{\text{75R min}} = \frac{Z \left( \frac{3}{0.0028+0.21} \sqrt{\frac{(2375-1125P/D)P_D}{4.123N_{p}D^3(S_c + D^2 N_p^2/12.788)}} \right)}{2.073 A_E/A_O}
\]  

(4.9)

where:

- \(D\) = propeller diameter (ft);
- \(P_D\) = delivered power (hp);
- \(N_p\) = propeller revolution rate (rpm);
- \(S_c\) = propeller material allowable stress (psi);
- \(P/D\) = pitch-diameter ratio.

However, in Chapter VI of this thesis, an algorithm which employs the Schoenherr formulation [Ref. 8] with some modifications, is presented as an alternative to equation (4.9).

C. THE DESIGN VECTOR

In view of the preceding presentations on optimization and powering, the design vector \(D\) can be assembled for the general propeller selection problem utilizing the B-Screw Series. This vector is composed of preassigned parameters relating to environmental conditions, hull characteristics
and the propeller which are required for various equations and the design variables.

1. **Parameters**
   
a. **Environmental**

   These parameters pertain primarily to the fluid conditions in which the propeller operates and to the atmosphere. Required for various calculations, they are:
   
   1) fluid temperature (°F)--Temp
   2) fluid density (lbf sec²/ft⁴)--ρ
   3) fluid viscosity (ft²/sec)--ν
   4) fluid vaporization pressure (psia)--p_watvap
   5) atmospheric pressure (psia)--p_atm

   b. Hull Characteristics

   These parameters pertain to certain details prescribed for the hull under study in the powering analysis. They are:
   
   1) wake fraction--wt
   2) thrust deduction--td
   3) relative rotative efficiency --n_R
   4) number of propellers--noscrw
   5) shaft centerline depth (ft)--h_CL
   6) propeller diameter limit (ft)--D_lim

   c. Propeller

   These parameters are specified in view of their discrete-valued nature. They are:
   
   1) number of blades--Z
   2) material--promat
Table (II) lists materials and properties considered in this study. These values are taken from Table (35), Section 15 of Reference [16].

**TABLE II**

<table>
<thead>
<tr>
<th>promat</th>
<th>Material</th>
<th>Allowable Stress--Sc (psi)</th>
<th>Density--wd (lbf/in³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Cast Iron</td>
<td>3600--3950</td>
<td>.260</td>
</tr>
<tr>
<td>2</td>
<td>Cast Steel</td>
<td>5915--6265</td>
<td>.289</td>
</tr>
<tr>
<td>3</td>
<td>Type 2 Bronze</td>
<td>7200-7585</td>
<td>.305</td>
</tr>
<tr>
<td>4</td>
<td>Type 4 Ni-Al Bronze</td>
<td>8910--9430</td>
<td>.278</td>
</tr>
<tr>
<td>5</td>
<td>Stainless Steel</td>
<td>5400--5500</td>
<td>.283</td>
</tr>
</tbody>
</table>

2. **Design Variables**

In view of equations (3.13) through (3.17), the design variables common to all selection approaches are:

1) \( P_E \)
2) \( V \)
3) \( D \)
4) \( P/D \)
5) \( A_E/A_O \)
6) \((t^*/c)\).75R
7) \( N_p \)
8) \( Q_S \)

The vectors \( \bar{D} \) and \( \bar{X} \) are shown schematically in figure (4.1).
Figure 4.1 Design Vectors $\bar{D}$ and $\bar{X}$
D. CONSTRAINTS

Besides the constraints imposed by equations (4.2), (4.5) and (4.8), equations (3.25) through (3.31) are rearranged to the format of constraints in equation (2.9). They are listed as follows:

1) Equivalent Reynolds Number—Equation (3.25) becomes:

\[ 1 \leq \frac{Rn* \cdot 75R}{2 \times 10^6} \leq 1000 \] \hspace{1cm} (4.10)

Two constraints are derived:

\[ G_3(\bar{X}) = 1 - \frac{Rn* \cdot 75R}{2 \times 10^6} \leq 0 \] \hspace{1cm} (4.11)

\[ G_4(\bar{X}) = \frac{Rn* \cdot 75R}{2 \times 10^6} - 1000 \leq 0 \] \hspace{1cm} (4.12)

2) Expanded Area Ratio—Equations (3.27) through (3.31) become:

\[ \frac{A_E}{A_O} \text{lower}(z) \leq \frac{A_E}{A_O} \leq \frac{A_E}{A_O} \text{upper}(z) \] \hspace{1cm} (4.13)

Two constraints are derived:

\[ G_5(\bar{X}) = \left( \frac{A_E}{A_O} \right) \text{lower}(z) - \frac{A_E}{A_O} \leq 0 \] \hspace{1cm} (4.14)

\[ G_6(\bar{X}) = \frac{A_E}{A_O} - \left( \frac{A_E}{A_O} \right) \text{upper}(z) \leq 0 \] \hspace{1cm} (4.15)
3) Advance Ratio--Equation (3.22) becomes:

\[ 0 \leq \frac{J}{1.6} \leq 1 \quad (4.16) \]

Two constraints are derived:

\[ G_1(\bar{x}) = \frac{-J}{1.6} \leq 0 \quad (4.17) \]

\[ G_2(\bar{x}) = \frac{J}{1.6} - 1 \leq 0 \quad (4.18) \]

4) Equivalent Blade Section Maximum Thickness-to-Chord Ratio--Using equation (3.19), boundaries on the range of \((t^*/c)_{.75R}\) are defined by:

\[ \frac{1}{2}(t/c)_{.75R} \leq (t^*/c)_{.75R} \leq 4(t/c)_{.75R} \quad (4.19) \]

Two constraints are derived:

\[ G_7(\bar{x}) = \frac{1}{2}(t/c)_{.75R} - (t^*/c)_{.75R} \leq 0 \quad (4.20) \]

\[ G_8(\bar{x}) = (t^*/c)_{.75R} - 4(t/c)_{.75R} \leq 0 \quad (4.21) \]

E. OBJECTIVE FUNCTIONS

Upon consideration of equation (3.13), Design Case No. 1 and Design Case No. 2 require that the open water efficiency \((\eta_o)\), given by equation (3.11), be maximized. In terminology related to optimization, this is stated as:
Design Case No. 3, the "matching" problem, requires that the blade weight (bldwt) be minimized. This is stated as:

\[ \text{OBJ}_3 = \text{bldwt} \quad (4.23) \]

F. PROPELLER SELECTION OPTIMIZATION PROBLEM STATEMENT

As a general, non-linear constrained optimization problem to be solved by COPES/CONMIN, the propeller selection problem for all Design Cases may be stated as one equation given by:

\[
\begin{align*}
\text{Minimize:} & \quad F(\overline{X}) = \text{OBJ}_{1,2} \quad \text{or} \quad \text{OBJ}_3 \\
\text{Subject to:} & \quad G_j(\overline{X}) \leq 0 \quad j = 1, \ldots, 12 \\
& \quad X_{\text{lower}}^i \leq X_i \leq X_{\text{upper}}^i \quad i = 1, \ldots, 8
\end{align*}
\]

The constraint \( G_{12}(\overline{X}) \) and the values for \( X_{\text{lower}}^i \) and \( X_{\text{upper}}^i \) will be specified according to each Design Case.

G. CODING FUNDAMENTALS

1. GLOBCM Common Block

The GLOBCM common block, required by COPES/CONMIN, is now assembled. Table (III) specifies the assignment locations for the FORTRAN variables which define objective functions, design variables and constraints.

2. SUBROUTINE ANALIZ

While each Design Case uses a different approach, all analyses are very similar. Therefore, each SUBROUTINE
<table>
<thead>
<tr>
<th>Global Location</th>
<th>FORTRAN Name</th>
<th>DEFINITION</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>ETAO</td>
<td>$n_0$</td>
</tr>
<tr>
<td>2</td>
<td>WEIGHT</td>
<td>bldwt</td>
</tr>
<tr>
<td>3</td>
<td>AEDVAO</td>
<td>$A_E/A_O$</td>
</tr>
<tr>
<td>4</td>
<td>DIA</td>
<td>D</td>
</tr>
<tr>
<td>5</td>
<td>N</td>
<td>$N_P = 60 \cdot n_P$</td>
</tr>
<tr>
<td>6</td>
<td>PE</td>
<td>$P_E$</td>
</tr>
<tr>
<td>7</td>
<td>PDIVD</td>
<td>P/D</td>
</tr>
<tr>
<td>8</td>
<td>QS</td>
<td>$Q_S$</td>
</tr>
<tr>
<td>9</td>
<td>TC75R</td>
<td>$(t*/c)\cdot75R$</td>
</tr>
<tr>
<td>10</td>
<td>V</td>
<td>V (ft/sec)</td>
</tr>
<tr>
<td>11</td>
<td>RJCHL</td>
<td>$G_1(\bar{x})$ -- eqn (4.17)</td>
</tr>
<tr>
<td>12</td>
<td>RJCNU</td>
<td>$G_2(\bar{x})$ -- eqn (4.18)</td>
</tr>
<tr>
<td>13</td>
<td>R75RCL</td>
<td>$G_3(\bar{x})$ -- eqn (4.11)</td>
</tr>
<tr>
<td>14</td>
<td>R75RCU</td>
<td>$G_4(\bar{x})$ -- eqn (4.12)</td>
</tr>
<tr>
<td>15</td>
<td>AEAOCL</td>
<td>$G_5(\bar{x})$ -- eqn (4.14)</td>
</tr>
<tr>
<td>16</td>
<td>AEAOCU</td>
<td>$G_6(\bar{x})$ -- eqn (4.15)</td>
</tr>
<tr>
<td>17</td>
<td>TC75CL</td>
<td>$G_7(\bar{x})$ -- eqn (4.20)</td>
</tr>
<tr>
<td>18</td>
<td>TC75CU</td>
<td>$G_8(\bar{x})$ -- eqn (4.21)</td>
</tr>
<tr>
<td>19</td>
<td>POWBAL</td>
<td>$G_{12}(\bar{x})$ -- eqn (7.10) or (8.11) or (9.4)</td>
</tr>
<tr>
<td>20</td>
<td>DIACNU</td>
<td>$G_9(\bar{x})$ -- eqn (4.2) or (9.6)</td>
</tr>
<tr>
<td>21</td>
<td>AEAOCV</td>
<td>$G_{10}(\bar{x})$ -- eqn (4.5)</td>
</tr>
<tr>
<td>22</td>
<td>TCSTRS</td>
<td>$G_{11}(\bar{x})$ -- eqn (4.8)</td>
</tr>
<tr>
<td>23</td>
<td>RJ</td>
<td>J</td>
</tr>
</tbody>
</table>

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ANALIZ shares a common structure and other common subroutines which perform calculations required in all cases. Appendices C, F and I contain, respectively, the source listings of SUBROUTINE ANALIZ for Design Case No. 1, Design Case No. 2 and Design Case No. 3.

a. Structure

The structure common to all cases follows accordingly:

1) all initialization of environmental, hull and propeller parameters is accomplished in the input section (ICALC = 1).

2) evaluation of $K_T$ and $K_Q$, all constraints and appropriate objective functions ($-\eta_Q$ or bldwt) are accomplished in the execution section (ICALC = 2).

3) output of results for each optimization problem is accomplished in the output section (ICALC = 3).

b. Basic Subprograms

The following FORTRAN subprograms are used in all three SUBROUTINE ANALIZ codes:

1) SUBROUTINE CH75RA--calculates the equivalent blade section chord length ($c_{.75R}$) for the propeller using Table 1 [Ref. 2, p. 252].

2) SUBROUTINE REY75R--calculates the equivalent Reynolds number ($Rn_{.75R}$) using equations (3.19) and (3.20).

3) SUBROUTINE COEFSA--calculates the thrust and torque coefficients ($K_T$ and $K_Q$) through sequential calls to SUBROUTINE CALCKT and SUBROUTINE CALCKQ. The polynomial expressions
Tables (5) and (6), [Ref. 2)] for these coefficients are contained in SUBROUTINE CALCKT and SUBROUTINE CALCKQ respectively.

4) SUBROUTINE OPWEFF--calculates the open water efficiency ($\eta_0$) using equation (3.11).

5) SUBROUTINE JCNA--calculates the constraints on the advance ratio (J) given by equations (4.17) and (4.18).

6) SUBROUTINE REYCNA--calculates the equivalent Reynolds number constraints given by equations (4.11) and (4.12).

7) SUBROUTINE EXTCCN--calculates the constraints on expanded area ratio ($A_E/A_0$) and equivalent blade section maximum thickness-to-chord ratio ($t*/c_{.75R}$) given by equations (4.14), (4.15), (4.20) and (4.21).

8) SUBROUTINE DICNUA--calculates the constraint on the propeller diameter (D) given by equation (4.2) using the hull parameter on maximum diameter ($D_{lim}$).

9) SUBROUTINE CAVCNA--calculates the constraint for cavitation given by equation (4.5) using equation (4.3).

10) SUBROUTINE STRCNA--calculates the constraint for strength given by equation (4.8) using equation (4.9).

H. SUMMARY

The propeller selection problem has now been formulated as a constrained optimization problem which can be solved by COPES/CONMIN. Two items remain for discussion before proceeding to specify the final details pertaining to each SUBROUTINE ANALIZ code and to present numerical examples. These items are:
1) the theory and coding relating to the computation of the propeller's blade weight for the evaluation of the objective function in Design Case No. 3 (OBJ₃).

2) the theory and coding relating to the computation of the minimum required equivalent blade section maximum thickness-to-chord ratio \( t^*/c_{.75 \text{ min}} \) for use in the alternative evaluation of the strength constraint given by equation (4.8).
V. PROPELLER BLADE WEIGHT--AN OBJECTIVE FUNCTION

A. INTRODUCTION

In this chapter, the method for the computation of the propeller's blade weight (bldwt), the objective function OBJ, is examined. First, a brief overview on the steps in the computational procedure is presented. The FORTRAN subprogram SUBROUTINE WGTICAL developed from the algorithm is then described. Again, Appendix B contains all subprogram listings.

B. THEORY AND PROCEDURE

Given the material of a propeller, the calculation of the weight of one blade involves nothing more than a volume calculation, a relatively routine task performed by most naval architects/marine engineers. Analogous to the determination of the underwater volume of a ship's hull, the calculation is an integration of blade section profiles' cross-sectional areas over the propeller radius (R).

1. Limits of Integration

Figure (5.1) depicts a side elevation view of a blade and hub, parallel to the propeller shaft axis. The cross-hatched area indicates the trace of the volume to be calculated. In view of equations (3.32) and (3.33), limits of integration are from \( r = 0.167R \) to \( r = R \) for \( Z = 4, 5, 6 \) and \( r = 0.18R \) to \( r = R \) for \( Z = 3, 7 \). For convenience, a non-dimensional variable "x" will be defined as:
Figure 5.1  Propeller Blade & Hub--Side View
Limits are now expressed as $x = 0.167$ or $0.18$ to $x = 1.0$.

Quite obviously, $R = (D/2.0)$.

2. **Blade Section Profile**

Figure (5.2) depicts an expanded cylindrical blade section in profile view at a given $r$ or $x$. For the Wageningen B-Screw Series, the profile is defined, geometrically, by a succession of vertical ordinates which specify points along the blade section's profile on the "face" ($y_f$) and on the back ($y_b$) with respect to the pitch reference line. At any $r = xR$, vertical ordinates for "aft" ($P < 0$) and "fwd" ($P > 0$) portions of the blade section are determined by:

\[
Y_{fa} = V_1(t^* - t^*_{te}) \quad P < 0 \quad (5.2)
\]

\[
Y_{ba} = (V_1 + V_2)(t^* - t^*_{te}) + t^*_{te} \quad P < 0 \quad (5.3)
\]

and

\[
Y_{ff} = V_1(t^* - t^*_{le}) \quad P > 0 \quad (5.4)
\]

\[
Y_{bf} = (V_1 + V_2)(t^* - t^*_{le}) + t^*_{le} \quad P > 0 \quad (5.5)
\]

where:

\[
V_1, V_2 = \text{tabulated values depending on } x \text{ and } P \\
\text{(see Tables (2) and (3), Ref. [2])};
\]
\[ t_{le} = \text{blade section leading edge thickness (ft)}; \]
\[ t_{te} = \text{blade section trailing edge thickness (ft)}. \]

Units for \( y_{fa}, y_{ba}, y_{ff} \) and \( y_{bf} \) are feet (ft). For this study, a reasonable assumption is made in that:

\[ t_{le} = t_{te} = (\frac{1}{10}) t^{*} \]  \hspace{1cm} (5.6)

3. **Blade Section Cross-Sectional Area**

The cross-sectional area at each \( x = r/R \) \( (A(x)) \) is determined by:

\[ A(x) = \sum_{i=1}^{9} A_{ai} + \sum_{i=1}^{10} A_{fi} \] \hspace{1cm} (5.7)

where

\[ A_{ai} = \Delta P_{ai} \frac{h_{ai+1} + h_{ai}}{2} \] \hspace{1cm} (5.8)
\[ h_{ai} = y_{bai} - y_{fai} \] \hspace{1cm} (5.9)
\[ h_{ai+1} = y_{bai+1} - y_{fai+1} \] \hspace{1cm} (5.10)

Expressions for \( A_{fi}, h_{fi} \) and \( h_{fi+1} \) follow in similar fashion.

Values for \( y_{fai} \) and \( y_{bai} \) are determined at 9 points along the "aft" portion of a given blade section's chord (c); values of \( y_{ffi} \) and \( y_{bfi} \) are determined at 10 points along the
"fwd" portion. The values for $\Delta P_{ai}$ and $\Delta P_{fi}$ are fractional values of the blade section's chord length ($c$) at radius $r = xR$ as determined from Tables (2) and (3) in Reference [2]. The units for $A(x)$ are square feet ($ft^2$). Units for $h_{ai}$, $h_{ai+1}$, $h_{fi}$, $h_{fi+1}$, $c$, $\Delta P_{ai}$ and $\Delta P_{fi}$ are feet ($ft$).

4. Volume Integration

The blade volume ($bldvol$) is finally determined by using Simpson's Rule for integration of $A(x)$ along the non-dimensional radius $x$ using appropriate limits.

5. Blade Weight

Once the blade volume ($bldvol$) is calculated, the weight ($bldwt$) is determined by:

$$bldwt = bldvol \cdot wd \cdot 1728$$  \hspace{1cm} (5.11)

where:

$$bldvol = \text{volume of one blade (ft}^3\text{)};$$
$$wd = \text{material weight density (lbf/in}^3\text{).}$$

Weight Density ($wd$) depends on blade material (promat). Table (II) lists appropriate values.

C. CODING

SUBROUTINE WGTCL is the main subprogram for the blade weight calculation. It, in turn, calls the following FORTRAN subprogram for various calculations:
1) SUBROUTINE TDIST--generates, at specified radius values, a distribution of blade section maximum thicknesses (t*).

2) SUBROUTINE BLDPRP--generates, at specified radius values (i.e., r = .167R or .18R, .2R, .3R, .4R, ..., .9R, 1.0R), various "blade section properties", one of which is a blade section's cross-sectional area given by equation (5.7). Other properties which are determined (for later use in direct stress computations) include blade section chord lengths and centroids and "critical point" locations as defined in Chapter VI.

3) SUBROUTINE BLDVOL --performs a Simpson's Rule integration for the propeller blade volume (bldvol) using blade section cross-sectional areas generated in SUBROUTINE BLDPRP. The blade weight (bldwt) is computed as a final step in the main subprogram SUBROUTINE WGTGAL.

Examination of the codes in Appendix B reveals extensive use of common blocks for passing data from one subprogram to another. Comment cards provide a full definition of all common blocks as well as a description of the task being performed at various points in a given subprogram.

D. SUMMARY

The coding developed for this study is, admittedly, not very compact and efficient. However, the intention has been to write all codes with sufficient documentation in order to facilitate the reader's understanding of the algorithms employed as well as to make the author's debugging work easier.
VI. THICKNESS-TO-CHORD RATIO--A DESIGN CONSTRAINT

A. INTRODUCTION

The purpose of this chapter is to examine the development of an algorithm that will be used to determine the minimum required equivalent blade section maximum thickness-to-chord ratio used in equation (4.8). The formulation is based upon the method developed by Dr. Karl E. Schoenherr [Ref. 8] in 1963. After a review of the past and present methods employed in propeller strength analysis is conducted, a description of the Schoenherr model and a list of the assumptions used with that model is presented. Then, a brief restatement of his model's equations which are used in the algorithm is followed by a derivation of the author's modifications to the Schoenherr method. The chapter is completed by conducting a review of the theory and coding employed by the algorithm.

The principal reference which is cited throughout this chapter is, again, Reference [8]. The reader is encouraged to review this reference for further details.

B. PROPELLER STRENGTH ANALYSIS--A HISTORICAL REVIEW

Marine propeller blades present a special class of structural problem. That problem lies in the difficulty of describing a blade design in simple mathematical terms for subsequent analysis through various means. Until the "finite element method era", analytical methods, including the one
adapted for this study, relied heavily on practical experience of the propeller designer and semi-theoretical considerations. Analysis by these methods provided a criterion of stress rather than actual computation of stresses. These methods for predicting blade stresses were developed by using "beam" theory or "shell" theory.

The use of elementary beam theory in propeller strength analysis was first adopted by Taylor [Ref. 22]. He treated a blade as a cantilever beam attached to the propeller hub and loaded by thrust and torque forces distributed linearly over the propeller radius. His approach is often deemed a "modified beam theory" because he chose to calculate the direct stresses using the moment of inertia properties of expanded cylindrical blade sections with neutral axis parallel to the nose-tail (pitch-reference) line or chord of that expanded section. Reasonable estimates of stresses along the blade surface were achieved for the unraked, unskewed and narrow-bladed propellers of his time.

As propellers "modernized" and became skewed and wider with increasing rake (mostly aft), modifications, improvements and alternatives to Taylor's theory were developed. Principally, modifications by Rosingh [Ref. 23] and Hancock [Ref. 24] proposed using moment of inertia properties of a blade section that was normal to the generating line of the axially projected blade outline. Romson [Ref. 25] later improved Taylor's theory for application to wide-bladed
propellers. Morgan [Ref. 26] provided an improved method for calculating the geometric properties of "modern" airfoil-shaped blade sections. Aeroldus and Keyser's [Ref. 27] "quasi-static" modeling of the propeller blade allowed for additional consideration to stresses induced by centrifugal loading of the raked and skewed blade. The beam theory approaches to propeller blade stress analysis culminated, for all practical purposes, with Schoenherr's work [Ref. 8] in 1963.

Alternatives to Taylor's beam theory approach, prior to 1963, consisted of the application of "shell" theory to the propeller blade strength problem. This approach was first proposed by Conn [Ref. 28] and subsequently formulated by Cohen [Ref. 29] who modeled the blade as a helicoidal shell with variable thickness and infinite width. "Shell Theory" was utilized again in experimental studies by Connolly [Ref. 30] who, like his predecessors, was also forced into making an assumption about the behavior of the displacements of the blade sections (i.e., constant displacements normal to the constant pitch blade at each fractional radius distance from the hub) beyond usual assumptions of shell theory. Essentially, his experimental results on one specific propeller contradicted the computational values. Attempts at a generalized numerical solution to Connolly's equations appeared in 1963 [Ref. 31] and 1964 [Ref. 32]. In 1968, Atkinson [Ref. 33], compared Connolly's results with currently
adopted cantilever beam methods and found, based on the inconsistency of results, that it was not possible to recommend one method over the other in the blade strength design procedure; another approach was needed.

Commenting on Atkinson's paper at that time, Sontvedt [Ref. 34] pointed out that, in view of these inconsistencies, the only approach to blade strength analysis which did not require very broad assumptions was the finite element technique. Developments in the method at that time were providing a new and powerful tool for structural analysis. The propeller blade was just another application. Genalis [Ref. 35] developed codes for the determination of displacements and stresses in a blade under hydrodynamic loads using the FEM technique and modeling the blade as a shell, a 3-D element mesh of tetrahedrons and rectangular prisms and, finally, a composite of shell and 3-D elements. As an aside, a finite "difference" solution to Connolly's analytical equations was proposed in 1972 [Ref. 36]. In 1973, Atkinson [Ref. 37] reported the application of both hydrodynamic and centrifugal loads to a blade modeled by a thin-shell triangular mesh and a thick-shell parabolic and cubic curved element mesh. The results of the triangular element were considered unsatisfactory. Another use of the thin-shell triangular element was reported by Sontvedt [Ref. 34] in 1974 using the SESAM-69 code [Ref. 38].

The need to model the blade correctly near the hub, where root stresses are usually critical, necessitated the
consideration of 3-D elements in lieu of thick/thin-shell elements [Refs. 39,40]. The use of the 4- and 10-noded tetrahedral element (i.e., TET-4, TET-10 respectively) to construct a blade mesh was conducted by Beek [Refs. 41,42]. He observed that improved accuracy of stress values, achieved by the use of these meshes, were overshadowed somewhat by the extensive storage capacity required for each analysis. Another "natural" improvement, from a geometrical standpoint, appeared in 1978. A general 3-D curved isoparametric element was incorporated in a computer code [Ref. 43] developed by Ma based on his previous formulation work [Ref. 44].

The finite element approach will continue to grow in use in propeller blade strength analysis with each successive improvement made to the basic elements which are used in the mesh generation of the blade. But, until the computer storage problem is resolved to the point where one mesh generation and subsequent stress analysis of one particular blade becomes a minor processing task, the basic analytical techniques will continue to be a meritable "check" [Ref. 45] in the preliminary (or conceptual) phase of propeller selection/design. In this context, the method formulated by Schoenherr and his colleagues twenty years ago is considered for adoption in determining a minimum required blade section maximum thickness-to-chord ratio.
C. SCHOENHERR'S METHOD

1. Background

Schoenherr's method is applicable to preliminary (or, conceptual) propeller selection problems because it employs an assumed thrust and torque force loading distribution for the propeller blade. This assumption is made at this stage of the ship's design because the exact wake velocity distribution at the propeller race is generally not known.

Also, his method is applicable to propellers represented by the Wageningen B-Screw Series because the blades of these propellers meet Schoenherr's criteria for the blade types covered by his formulation. Specifically, B-Screw Series blades have:

1) a small constant rake angle of 15° over the entire blade radius;
2) a constant pitch distribution over the propeller radius with the exception of the \( Z = 4 \) propeller whose pitch is slightly reduced near the hub;
3) mild skew;
4) linear distribution of blade section maximum thickness over the radius of the blade;
5) aerfoil profile qualities where the nose-tail line or the chord of the blade section is approximately parallel to the pitch reference line.
2. **The Blade Model**

Schoenherr models the propeller blade as a cantilever beam with unsymmetrical and variable area cross sections subjected to loading distributions of hydrodynamic and centrifugal forces. The following additional assumptions apply:

1) **Flexure theory applies.** This subsequently implies the following: a) plane cross sections remain plane under load, b) Hooke's Law is valid, c) the blade material is homogeneous and isotropic, d) fibers are free to extend and contract independently of adjacent fibers, and e) stresses at a point arising from various forces superimpose.

2) **Shearing stresses and their effects are neglected.** Only the direct stresses on a strength section are taken into account.

3) **The strength sections are taken to be the expanded cylindrical blade sections at various radial locations.**

4) **The neutral axes of a strength section are straight lines passing through the centroid of the expanded cylindrical blade section and are parallel and normal, respectively, to the pitch reference line, and therefore, the chord, at each blade section.**

5) **Bending Moments are applied in two planes which are mutually perpendicular to each other.** One plane is normal to the pitch-reference line (and chord) of the strength section; the other is parallel.

6) **The angle between the principal axes of inertia and the neutral axes is zero.**
Using this model and assumptions, Schoenherr applies the following formula for the evaluation of the direct fiber stress \( \sigma_o \) in a blade section at a radius \( r = r_o \):

\[
[\sigma]_o = \frac{[M]_{no} u_o}{I_{no}} + \frac{[M]_{lo} w_o}{I_{lo}} + \frac{[F_c]_o}{A(x_o)}
\] (6.1)

where:

- \( [M]_{no} \), \( [M]_{lo} \) = resultant bending moments in planes normal \( (\{M\}_{no}) \) and parallel \( (\{M\}_{lo}) \) to the strength section's chord at \( \bar{r} = r_o \) (ft-lbf);
- \( [F_c]_o \) = centrifugal force acting normal to the plane of the strength section at \( r = r_o \) and resulting from the centrifugal acceleration of the remaining blade element mass above that strength section (lbf);
- \( u_o, w_o \) = coordinates of a point on the strength section's periphery with respect to that section's neutral axes system \( (\ell-n \ system) \) (ft);
- \( A(x_o) \) = strength section's cross-sectional area (ft²);
- \( I_{lo} \) = moment of inertia of the strength section with respect to the "\( l \)" axis (ft⁴);
- \( I_{no} \) = moment of inertia of the strength section with respect to the "\( n \)" axis (ft⁴);
- \( x_o \) = non-dimensional radius given by \( x_o = r_o/R \).

Since equation (6.1) indicates that the direct fiber stress is greatest at points on the periphery of the strength section, Schoenherr selects to examine four "critical points"
on the periphery where the fiber stress is likely to be a maximum. These points are designated as \(1, 2, 3\) and \(4\) on Figure (6.1) and are specified by coordinates \((u_1, w_1), (u_2, w_2), (u_3, w_3)\) and \((u_4, w_4)\) respectively in the "\(l-n\)" reference system.

The values for \([M]_{no}\) and \([M]_{lo}\) are determined by the following relation:

\[
[M]_{no} = [M_p]_{no} + [M_{cb}]_{no} \tag{6.2}
\]

\[
[M]_{lo} = [M_p]_{lo} + [M_{cb}]_{lo} \tag{6.3}
\]

where:

\([M_p]_{no}\) = total bending moment due to hydrodynamic loading acting in a plane normal to a strength section's chord at \(r = r_0\) (ft-lbf);

\([M_p]_{lo}\) = total bending moment due to hydrodynamic loading acting in a plane parallel to a strength section's chord at \(r = r_0\) (ft-lbf);

\([M_{cb}]_{no}\) = total bending moment due to centrifugal loading acting in a plane normal to a strength section's chord at \(r = r_0\) (ft-lbf);

\([M_{cb}]_{lo}\) = total bending moment due to centrifugal loading acting in a plane parallel to a strength section's chord at \(r = r_0\) (ft-lbf).

3. **Bending Moments Due to Hydrodynamic Loading**

The derivations of \([M_p]_{no}\) and \([M_p]_{lo}\) follow directly from Part I of Schoenherr's paper [Ref. 8: p. 83-89] and,
Figure 6.1  Strength Section at $r = r_0$
therefore, only key equations will be restated. References
to equations which contain no decimal point apply to equations
as numbered in his paper.

Thrust and torque force are components of the hydro-
dynamic "lifting" force acting on a blade. Using an assumed
non-linear distribution of thrust along the blade radius
given by equation (2), Schoenherr derives the following ex-
pression for the bending moment due to thrust ([M_t]_o) which
acts at a blade section located at radius r = r_o:

\[ [M_t]_o = \frac{TR}{z} \cdot \frac{\phi_2(x_o)}{\phi_1(x_h)} \]  
(6.4)

where:

- \( T \) = propeller thrust (lbf);
- \( R \) = propeller radius (ft);
- \( z \) = no. of blades;
- \( \phi_2(x_o), \phi_1(x_h) \) = functions of non-dimensional
  radius \( x \) evaluated at \( x = r_o/R \)
  and \( x_h = 0.2 \) and given by equa-
tions (4) and (9).

For the bending moment due to torque ([M_q]_o) which
acts at a blade section located at radius \( r = r_o \), Schoenherr
derives the following:

\[ [M_q]_o = \frac{Q_p}{z} \cdot \frac{\psi_2(x_o)}{\phi_1(x_h)} \]  
(6.5)

where:
\[ Q_p = \text{propeller torque (ft-lbf);} \]

\[ Z = \text{no. of blades;} \]

\[ \psi_2(x_o), \phi_1(x_h) = \text{functions of non-dimensional radius x evaluated at } x_o = r_o/R \text{ and } x_h = 0.2 \text{ and given by equations (19) and (4).} \]

Figure (6.2) depicts the component resolution for \([M_p]_{no}\) and \([M_p]_{zo}\) which results when equations (6.4) and (6.5) are imposed at a strength section at \(r = r_o\) which has a pitch angle \(\beta_o\). The following relations are derived as equations (42) and (43) in Schoenherr's paper:

\[ [M_p]_{no} = [M_t]_o \cos \beta_o + [M_q]_o \sin \beta_o \quad (6.6) \]

\[ [M_p]_{zo} = [M_t]_o \sin \beta_o - [M_q]_o \cos \beta_o \quad (6.7) \]

4. Force and Bending Moments Due to Centrifugal Loading

The derivation and expressions contained in this section constitute the author's modifications to the formulation in Part II of Schoenherr's paper. In Part II, Schoenherr's derivations for \([M_{cb}]_{no}\) and \([M_{cb}]_{zo}\) are formulated for computation using a propeller drawing. This follows from the fact that his method, which was funded by the American Bureau of Shipping, was intended to be used as that classification society's "designer's check" on adherence to the Bureau's strength criteria from a propeller blueprint. To evaluate the direct fiber stresses from equation (6.1) for the Wageningen B-Screw Series in accordance with Schoenherr's
Figure 6.2 Bending Moments due to Thrust and Torque
method, \([M_{cb}]_{n0}\) and \([M_{cb}]_{l0}\) must be evaluated from expressions derived from the available information on blade section profiles and other geometric characteristics which are contained in Reference [2] and previously used in Chapter V.

Consider Figure (6.3) where the centrifugal force \([C_F]_o\) of a blade element above a blade section at \(x = x_o = r_o/R\) acts in a radial direction from the shaft centerline. Its line of action passes through point "N", which is on the same cylindrical surface as the blade section at \(x = x_o = r_o/R\), and through point "G", which is the center of gravity of the blade element above the blade section at \(x = x_o = r_o/R\).

From the figure, the following expression is derived:

\[ [C_F]_o = [C_F]_o \cos \zeta(x_o) + [C_F]_o \sin \zeta(x_o) \quad (6.8) \]

\([C_F]_o\) is shifted to point "N" and is decomposed into components \([C_F]_o \cos \zeta(x_o)\) and \([C_F]_o \sin \zeta(x_o)\). The entire cylindrical surface in which the blade section at \(x = x_o = r_o/R\) and point "N" lie is now expanded into a flat plane for further consideration (see Figure (6.4)). In this configuration, \([C_F]_o \cos \zeta(x_o)\) is normal to this flat plane while \([C_F]_o \sin \zeta(x_o)\) lies in this plane.

Let point "O" be the location of the blade section's neutral axes system (i.e., the \(l\)-\(n\) system). Then, the forces and moments due to the centrifugal reaction of the blade element above this section act at point "O" and are given by:
\[
[F_c]_o = [C_F]_o \cos \zeta (x_o) \quad (6.9)
\]
\[
[D_c]_o = [C_F]_o \sin \zeta (x_o) \quad (6.10)
\]
\[
[M_{cb}]_o = [F_c]_o \cdot NO \quad (6.11)
\]
\[
[M_{cw}]_o = [D_c]_o \cdot LO \quad (6.12)
\]

where:

- \([F_c]_o\) = direct force, due to centrifugal action, acting on the blade section located at \(x = x_o = r_o/R\);
- \([D_c]_o\) = shear force, due to centrifugal action, acting on the blade section located at \(x = x_o = r_o/R\);
- \([M_{cb}]_o\) = bending moment at point "O" imposed by \([F_c]_o\) acting through point "N";
- \([M_{cw}]_o\) = torsional moment at point "O" imposed by \([D_c]_o\) acting through point "N".

Since Schoenherr's method does not consider shear forces and their effects, \([D_c]_o\) and \([M_{cw}]_o\) will not be considered in this modification. However, \([F_c]_o\) and \([M_{cb}]_o\) must now be computed for each blade section along the propeller's radius in order to account for their contributions to equations (6.2), (6.3) and, finally, in equation (6.1).

The computation is derived as follows. Consider Figure (6.4). Again, \([F_c]_o\) acts through point "N" and is normal (outward) to the plane of the figure. \([M_{cb}]_o\) is now resolved into components of the i-n axes system as follows:
\[ [M_{cb}]_{no} = [C_F]_o \cos \xi(x_o) \{ p_o \sin \beta_o + q_o \cos \beta_o + Y_{co} \} \quad (6.13) \]

\[ [M_{cb}]_{lo} = [C_F]_o \cos \xi(x_o) \{ q_o \sin \beta_o - p_o \cos \beta_o + X_{co} \} \quad (6.14) \]

where:

\[ \beta_o = \text{pitch angle of the blade section at} \ x = x_o = r_o/R; \]
\[ X_{co} = \text{distance of the blade sections centroid from} \ \text{the generator line (ft)}; \]
\[ Y_{co} = \text{distance of the blade section's centroid from} \ \text{the pitch reference line (ft)}; \]
\[ q_o = \text{distance to point "N" from point "P" parallel to the shaft axis at} \ x = x_o = r_o/R \ \text{(ft)}; \]
\[ p_o = \text{distance to point "N" from point "P" perpendicular to the shaft axis at} \ x = x_o = r_o/R \ \text{(ft)}. \]

The quantity \( \beta_o \) is found by the relation:

\[ \tan \beta_o = \frac{1}{\pi} \cdot (P/D)_o \quad (6.15) \]

For the Wageningen B-Screw Series, \( (P/D)_o \) is a constant along \( R \) except for propellers with \( Z = 4 \).

The quantity \( [C_F]_o \) is computed from the relation:

\[ [C_F]_o = 1728 \cdot \frac{wd v_o}{acg} \cdot (2\pi p_o)^2 \cdot R \cdot (\bar{X}_G)_o \quad (6.16) \]

where:
\[ V_o = \text{volume of the blade element above the blade section at } x = x_o = r_o/R \text{ (ft}^3) \];

\[ \text{acg} = 32.174 \text{ ft/sec}^2; \]

\[ \text{wd} = \text{material weight density (lbf/in}^3); \]

\[ n_p = \text{propeller revolution rate (rps);} \]

\[ (x_G)_o = \text{non-dimensional radial position of "G" for the blade element above the shaft axis;} \]

\[ R = \text{propeller radius (ft).} \]

At this point, only five quantities remain to be determined for the evaluation of the expressions of equations (6.10), (6.13) and (6.14). They are:

1) \( \cos \zeta(x_o) \)
2) \( p_o \)
3) \( q_o \)
4) \( (x_G)_o \)
5) \( V_o \)

These quantities are determined by integration over the blade element above the blade section, located at \( x = x_o = r_o/R \), from \( x = x_o \) to \( x = 1.0 \).

The values for \( p_o \) and \( q_o \) will vary with the location of "G" (from Figure (6.3)) which depends on \( x \). Consider a radially thin slice of the blade element above the blade section, located at \( x = x_o = r_o/R \) (see Figure (6.5)). This thin "slice" is located at a non-dimensional distance \( x \) from the shaft centerline where \( x_o < x < 1.0 \). Figure (6.6) depicts this section expanded onto a plane. Let "g" be the centroid of that "slice". If \( x_g \) is the distance from the generator...
Figure 6.5 Position of "g" of a Blade Section "Slice" at $x = r/R$. 

\[ \text{Diagram showing the position of "g" for a blade section with x normalized by R.} \]
Figure 6.6 Coordinates of centroid "G" of any Blade Section
line to "g" in feet and \( y_g \) is the distance from the pitch reference line in feet, then, from Figures (6.5) and (6.6), the following relations apply:

\[
i_g = x R \tan \eta \tag{6.17}
\]

\[
i_g - a_g = i_g - x_g \sin \beta_g - y_g \cos \beta_g \tag{6.18}
\]

\[
t_g = x_g \cos \beta_g - y_g \sin \beta_g \tag{6.19}
\]

where:

\[\eta = \text{rake angle at } x;\]

\[x_g = \text{distance of "g" from point "P" parallel to the shaft axis (ft);}\]

\[y_g = \text{distance of "g" from point "P" perpendicular to the shaft axis (ft).}\]

For the Wageningen B-Screw Series, rake angle \( \eta \) is a constant 15° everywhere along the radius \( R \).

Now, to compute the volume of the blade element above the blade section located at \( x = x_o = r_o/R \), the following expression is used:

\[
V_o = \int_{x=x_o}^{1} RA(x) \, dx \tag{6.20}
\]

To compute the non-dimensional radial position of "G" for the blade element above a blade section located at \( x = x_o = r_o/R \), the following expression is used:
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Naval Postgraduate School Monterey CA

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\[ (\bar{x}_G)_o = \frac{\int_{x=x_o}^{1} A(x) \, dx}{\int_{x=x_o}^{1} A(x) \, dx} \]  \hspace{1cm} (6.21)

To compute the tangential position of "G" for the blade element above a blade section located at \( x = x_o = r_o/R \), the following expression is used:

\[ T_o = \frac{\int_{x=x_o}^{1} A(x) \, t_g \, dx}{\int_{x=x_o}^{1} A(x) \, dx} \]  \hspace{1cm} (6.22)

And, finally, to compute the axial position of "G" for the blade element above a blade section located at \( x = x_o = r_o/R \), the following expression is used:

\[ A_o = \frac{\int_{x=x_o}^{1} A(x) (i_g-a_g) \, dx}{\int_{x=x_o}^{1} A(x) \, dx} \]  \hspace{1cm} (6.23)

Using the values just determined for \((\bar{x}_G)_o\), \(T_o\) and \(A_o\), the following expressions are used to evaluate \(p_o\) and \(q_o\):

\[ p_o = \frac{x_o}{(\bar{x}_G)_o} T_o \]  \hspace{1cm} (6.24)
\[ q_0 = A_0 - x_0 \tan \eta \]  

(6.25)

The expression for \( \cos \zeta(x_0) \) follows:

\[ \cos \zeta(x_0) = \frac{p_o}{x_0 R} \]  

(6.26)

The formulation is now complete. Equations (6.10), (6.13) and (6.14) can now be evaluated for any blade section located at \( x = x_0 = r_o / R \). From here, equations (6.2) and (6.3) are evaluated. Finally, using the results from these equations and equation (6.9), equation (6.1) can be evaluated for the four points, specified by coordinates \((u1,w1)\), \((u2,w2)\), \((u3,w3)\) and \((u4,w4)\), at any location \( x = x_0 = r_o / R \).

From the development discussed in Chapter V, the values for \( A(x) \), \( x_g \), \( y_g \), \( I_{no} \) and \( I_{z0} \) are readily available.

D. ALGORITHM FOR THE CONSTRAINT

1. Theory

Schoenherr's formulation with the modifications just derived can be used in determining the minimum required equivalent blade section maximum thickness-to-chord ratio \( ((t*/c) .75R \text{ min}) \) for use in the constraint \( G_{11}(X) \leq 0 \) given by equation (4.8). The procedure employed is as follows:

1) Assume an initial value for \((t*/c) .75R \text{ min}\) using equation (3.21);

2) Increase this value by a small amount;
3) using \((t*/c) .75R\) min obtained from step (2), generate a distribution of minimum required blade section thicknesses \(t_{\min}\) for blade sections at specified points along the propeller radius, say at \(r = .2R, .3R, .4R, .5R, .6R, .7R, .8R,\) and \(.9R;\)

4) determine all blade section properties to include:
   a) cross-sectional area, b) chord length, c) centroid location,
   d) moments of inertia with respect to the principal axes system (i.e., \(l-n\) system), e) coordinate values for the four critical points defined in the previous section;

5) compute the hydrodynamic bending moment components \([M_p]_n\) and \([M_p]_l\) at radius locations just specified;

6) compute the values of the centrifugal force \([F_c]_o\) and the bending moment components \([M_{cb}]_n\) and \([M_{cb}]_l\) acting on blade sections at radius locations just specified;

7) calculate the direct fiber stresses at all four critical points for all radius locations specified in step (3);

8) check the following condition on the calculated fiber stress at all four critical points at all specified radius locations using:

\[
[\sigma]_o \leq 144 \cdot S_c \quad (6.27)
\]

9) if the maximum allowable stress \((S_c)\) for the material is exceeded, then return to step (2) and repeat. Otherwise, proceed to next step.
10) since the minimum required equivalent blade section maximum thickness-to-chord ratio assumed in step (2) has produced blade sections of adequate strength, evaluate the constraint given by equation (4.8).

2. Coding Details

The algorithm just outlined is incorporated into the main FORTRAN subprogram SUBROUTINE STRCNK. This subprogram, in turn, executes the algorithm through sequential calls to other key FORTRAN subprograms. These subprograms are listed as follows:

1) SUBROUTINE TDIST--accomplishes step (3); generates, at specified radius values, a distribution of minimum required blade section maximum thicknesses \( t^{*}_{\text{min}} \) for the assumed value of \( (t^{*}/c) .75R_{\text{min}} \);

2) SUBROUTINE BLDPRP--accomplishes step (4); described previously in Chapter V;

3) SUBROUTINE HYDLD--accomplishes step (5); computes the hydrodynamic bending moment components, given by equations (6.6) and (6.7), at specified radius locations;

4) SUBROUTINE CNFGLD--accomplishes step (6); computes the centrifugal force and bending moments, given by equations (6.9), (6.13) and (6.14) respectively, at specified radius locations;

5) SUBROUTINE SIGNDS--accomplishes step (7); computes direct fiber stresses, given by equation (6.1), for all four critical points at every specified radius location.
During the remaining steps of SUBROUTINE STRCNK, the condition on allowable stress, given by equation (6.27), is checked at all critical points of blade sections located at specified radius locations (again, \( r = 0.2R, 0.3R, 0.4R, 0.5R, 0.6R, 0.7R, 0.8R \) and \( 0.9R \)). The final calculation made is that for the constraint given by equation (4.8).

Again, extensive use of common blocks, for passing data from one subprogram to another, is apparent upon examination of the codes just cited. Comment cards are used throughout.

E. SUMMARY

The end of this chapter marks the completion of all prerequisite background and formulation discussions on the application of COPES/CONMIN to propeller selection problems involving the Wageningen B-Screw Series. From this point, each specific Design Case can now be solved as an optimization problem.
VII. DESIGN CASE NO. 1--PROGRAMMING AND COMPARISONS

A. INTRODUCTION

In this chapter, COPES/CONMIN is used in the solution of propeller selection problems which use the "thrust" approach. First, the thrust approach to the propeller selection problem is formulated. Then, a review of a previous author's solution to this problem is presented. Four variations to this propeller selection problem are solved by COPES/CONMIN. The chapter is completed with a presentation and discussion of the results from the four variations.

B. THRUST APPROACH FORMULATION

1. Design Vector $\mathbf{X}_T$

As previously pointed out at the conclusion of Chapter III, Design Case No. 1 constitutes a propeller selection problem which is solved by the thrust approach. In this approach, the effective horsepower ($P_E$) and the ship's speed ($V$) are specified by the designer. From the viewpoint of optimization, the quantities $P_E$ and $V$ become preassigned parameters. This reduces the design vector $\mathbf{X}$ (see Figure 4.1) to:

$$
\mathbf{X} = \begin{pmatrix}
D \\
P/D \\
A_E/A_O \\
(t*/c) \cdot 75R \\
N_P \\
Q_S
\end{pmatrix}
$$

(7.1)
Having specified $P_E$ and $V$, all of the design variables, as listed in equation (7.1), are not independent. Recalling equations (3.3) and (3.13), the following relationship results:

$$P_E = \frac{(1-td)}{(1-wt)} \cdot \eta_R \cdot \eta_O \cdot \frac{2\pi Q_S}{550} \cdot \frac{N_p}{60} \quad (7.2)$$

Rearranging terms, this equation becomes:

$$\eta_O Q_S N_p = \frac{(1-wt)}{(1-td)} \cdot \frac{P_E}{\eta_R} \cdot \frac{550 \cdot 60}{2\pi} \quad (7.3)$$

Considering that the open water efficiency ($\eta_O$) is evaluated prior to the computation of ($-\eta_O$), or OBJ$_{1,2}$, then both $N_p$ and $Q_S$ are not independent design variables. One must be selected as the independent design variable. Then, the other variable becomes dependent on the one just selected.

For this study, $N_p$ is selected as the independent design variable. This choice will reduce the design vector $\bar{X}$ for propeller selection problems using the thrust approach to the following:

$$\bar{X} = \begin{pmatrix} D \\ P/D \\ \frac{A_E}{A_O} \\ \frac{(t^*/c) .75R}{N_p} \end{pmatrix} \quad (7.4)$$
Finally, equation (3.8) implies an alternative definition of $\bar{X}$ as given in equation (7.4). The design vector for Design Case No. 1 propeller selection problems is, therefore, defined as:

$$\bar{X}_1 = \begin{pmatrix} D \\ P/D \\ A_E/A_O \\ (t_*/c) .75R \\ J \end{pmatrix} \quad (7.5)$$

2. **Powering Constraint**

Having determined the design vector $\bar{X}_1$, a final restriction to the general propeller selection problem, as stated by equation (4.24), remains for consideration. This restriction constitutes the remaining constraint $G_{12}(\bar{X})$ mentioned in Chapter IV.

Simply stated, the selected propeller, as defined by $\bar{X}_1$, must develop enough thrust ($T$) so that the powering requirement, specified by $P_E$ and $V$, is met. Using equation (3.2), the thrust developed by the propeller can be specified in terms of thrust horsepower ($P_T$) as:

$$ (P_T)_{\text{dev}} = \frac{T \cdot V(1-wt)}{550} \quad (7.6) $$

From equation (3.9), it follows that:

$$ (P_T)_{\text{dev}} = \frac{\rho \cdot n^2 \cdot D^4 \cdot K_T}{550} \cdot V(1-wt) \quad (7.7) $$
Using equation (3.12), the developed thrust horsepower can be defined in terms of developed effective horsepower given by:

\[(P_E)^{\text{dev}} = \frac{(1-td)}{(1-wt)} \cdot (P_T)^{\text{dev}}\]  \hspace{1cm} (7.8)

The restriction imposed by the thrust approach method, where \(P_E\) and \(V\) are specified, can now be stated as:

\[P_E \leq (P_E)^{\text{dev}}\] \hspace{1cm} (7.9)

Rearranging equation (7.9), the constraint \(G_{12}(\overline{X})\) follows:

\[G_{12}(\overline{X}) = 1 - \frac{(P_E)^{\text{dev}}}{P_E} \leq 0\] \hspace{1cm} (7.10)

With the design vector \(\overline{X}\) and \(G_{12}(\overline{X})\) defined, the propeller selection problem represented by Design Case No. 1 can be stated under one equation as:

\[\text{Maximize: } F(\overline{X}) = OBJ_{1,2}\]

\[\text{Subject to: } G_j(\overline{X}) \leq 0 \quad j = 1, \ldots, 12\] \hspace{1cm} (7.11)

\[X_{1i}^{\text{lower}} \leq X_{1i} \leq X_{1i}^{\text{upper}} \quad i = 1, \ldots, 5\]

C. PREVIOUS SOLUTIONS

Triantafyllou [Refs. 3,21] considered a propeller selection problem represented by Design Case No. 1. In his example problem, the following parameters were specified:
1) \( v = 1.139 \times 10^{-6} \text{ (m}^2/\text{sec)} = 1.22613 \times 10^{-5} \text{ (ft}^2/\text{sec)} \)

2) \( \text{wt} = .22 \)

3) \( \text{td} = .19 \)

4) \( n_R = 1.025 \)

5) \( \text{noscrw} = 1 \)

6) \( Z = 5 \)

7) \( P_E = 18153 \text{ (hp)} \)

8) \( V = 24 \text{ (knots)} \)

9) \( D = 22.0 \text{ (ft)} \)

10) \( A_E/A_O = .85 \)

The hull under study in his example had the following dimensions:

1) Length = 710 (ft)

2) Draft = 30 (ft)

3) Beam = 100 (ft)

For his analysis, the design vector contained two variables and was specified as:

\[
\bar{X}^T = \begin{bmatrix} J \\ P/D \end{bmatrix}
\]

Using an iterative scheme [Ref. 21: p. 79] to solve two equations in two unknowns, he maximized the open water efficiency \( (n_o) \) to obtain the following results:

\[
P/D = 1.1651
\]

\[
N_p = 104 \text{ (rpm)}
\]
\[ P_D = 25544 \text{ (hp)} \]
\[ \eta_o = 0.6676 \]

For future comparisons, equations (3.8) and (3.3) give:

\[ J = 0.8286 \]
\[ Q_S = 1290000.0 \text{ (ft-lbf)} \]

Triantafyllou's results are summarized in Table (IV).

D. SOLUTIONS BY COPES/CONMIN

The propeller selection problem, as stated by equation (7.11), is now solved by COPES/CONMIN. Four solution variations are considered.

The first and second variations attempt to reproduce the solution given by Triantafyllou. The design vector \( \bar{X}_T \) (NDV = 2) is used in both cases. One variation uses SUBROUTINE STRCNA to evaluate the constraint \( G_{12}(\bar{X}_T) \) given by equation (4.8). The other uses SUBROUTINE STRCNK to determine \( G_{12}(\bar{X}_T) \).

The remaining two variations will solve the propeller selection problem using the design vector \( \bar{X}_T \) (NDV = 5) defined in equation (7.5). Again, one variation uses SUBROUTINE STRCNA; the other, SUBROUTINE STRCNK.

In all variations, the following parameters are used:

1) Temp = 59 (°F)
2) \( \rho = 1.9384 \text{ (lbf-sec}^2/\text{ft}^4) \)
3) \( v = 1.2285 \times 10 \text{ (ft}^2/\text{sec)} \)
4) $P_{\text{watvap}} = 0.247$ (psia)
5) $P_{\text{atm}} = 14.7$ (psia)
6) $w_t = 0.22$
7) $t_d = 0.19$
8) $\eta_R = 1.025$
9) noscrw = 1
10) $h = 19.0$ (ft)
11) $D_{\text{lim}} = 22.0$ (ft)
12) $Z = 5$
13) promat = 5 (stainless steel; see Table (II))
14) $P_E = 18153$ (hp)
15) $V = 24.0$ (knots)

All of the above are initialized in the input phase (ICALC = 1) of each SUBROUTINE ANALIZ pertaining to each variation.

The constraint $G_{12}(\tilde{\xi})$ or $G_{12}(\tilde{\xi}^T)$ is evaluated by SUBROUTINE BLPOW1 which appears in the execution section of each SUBROUTINE ANALIZ.

1. **Variation 1**
   a. Programming Details

Since this variation uses the design vector $\tilde{\xi}^T$, the following design variables of $\tilde{\xi}$ become parameters and are specified in the input section of SUBROUTINE ANALIZ (ICALC = 1) as:

1) $D = 22.0$ (ft)
2) $A_E/A_0 = 0.85$
3) $(t^*/c)_{0.75R} = 0.0348$ (from equation 3.21).
For constraints, the following are used:

\[ G_j(\mathbf{x_T}) \leq 0 \quad j = 1, \ldots, 8, 12 \]

Only nine of twelve constraints are evaluated (NCON = 9).

Obviously, some of the twelve constraints are redundant since 
\( D, \frac{A_E}{A_o}, \text{ and } (t^*/c)_{.75R} \) have been specified.

The upper (\( x_{i,\text{upper}} \)) and lower (\( x_{i,\text{lower}} \)) limits on the design variables \( J \) and \( P/D \) are set to be:

\[ .01 \leq J \leq 1.6 \]
\[ .4 \leq P/D \leq 1.4 \]

These upper and lower limits are specified in the COPES control card deck on card image F under respective fields VUB and VLB. The initial value for each design variable \( (x_{i,\text{ Igor}}) \) is also assigned on card image F under the field labeled X. The first list of card images in Appendix D lists all of the COPES control cards used for this variation and variation 2. These cards also specify the locations of the design variables in the common block GLOBCM (see Table (III)) as well as the locations of the constraints and their boundaries. Further details on the COPES control card requirements and the format of each card are contained in Reference [7].

An examination of SUBROUTINE ANALIZ for this variation, found in Appendix C, shows the calling statement made to SUBROUTINE STRCNA.
b. Results

The output from the optimization/analysis, performed by COPES/CONMIN, is listed first in Appendix E. Results for this variation of the propeller selection problem are tabulated in Table (IV).

2. Variation 2

a. Programming Details

Everything discussed above for the first variation applies here with one exception. An examination of SUBROUTINE ANALIZ for the second variation, found in Appendix C, shows the calling statement made to SUBROUTINE STRCNK.

b. Results

The output from the optimization/analysis, performed by COPES/CONMIN, is listed second in Appendix E. Results for this variation of the propeller selection problem are tabulated in Table (IV).

3. Variation 3

a. Programming Details

This variation uses the design vector $\mathbf{X}_1$. For constraints, the following are used:

$$ G_j(\mathbf{X}_1) \leq 0 \quad j = 1, \ldots, 12 $$

All twelve constraints are evaluated ($NCON = 12$).

The upper ($X_{1i}^{\text{upper}}$) and lower ($X_{1i}^{\text{lower}}$) limits on the design variables $D$, $P/D$, $A_E/A_O$, $(t*/c) .75R'$, and $\mathbf{J}$ are set as:
1.0 \leq D \leq 50.0 \text{ (ft)}

.4 \leq P/D \leq 1.4

.2 \leq A_E/A_O \leq 1.1

.003 \leq (t*/c)_R \leq .50

.01 \leq J \leq 1.6

These upper and lower limits are specified in the COPES control card deck on card image F under respective fields VUB and VLB. The initial value for each design variable ($X_l$) is also assigned on card image F under the field labeled $X$.

The second list of card images in Appendix D lists all of the COPES control cards used for this variation and variation 4. These cards also specify the locations of the design variables in the common block GLOBCM (see Table (III)) as well as the locations of the constraints and their boundaries.

Further details on the COPES control card requirements and the format of each card are contained in Reference [7].

An examination of SUBROUTINE ANALIZ for this variation, found in Appendix C, shows the calling statement made to SUBROUTINE STRCNA.

b. Results

The output from the optimization/analysis, performed by COPES/CONMIN, is listed third in Appendix E. Results for this variation of the propeller selection problem are tabulated in Table (IV).
4. Variation 4
   a. Programming Details

   Everything discussed above for the third variation applies here with one exception. An examination of SUBROUTINE ANALIZ for the fourth variation, found in Appendix C, shows the calling statement made to SUBROUTINE STRCNK instead of SUBROUTINE STRCNA.

   b. Results

   The output from the optimization/analysis, performed by COPES/CONMIN, is listed last in Appendix E. Results for this variation of the propeller selection problem are tabulated in Table (IV).

E. DISCUSSION

   Overall, the results achieved in all variations compare reasonably well to the solution obtained by Triantafyllou. However, the following points can be made.

   Variations 1 and 2 give the same results. This was expected in view of the fact that, even though constraints $G_9(\mathbf{xT})$ through $G_{11}(\mathbf{xT})$ were evaluated, these constraints were not considered in the optimization search conducted by CONMIN.

   In variations 3 and 4, the diameter ($D$) was driven to the limit ($D_{lim}$). This bears out a fundamental rule in propeller design, i.e., the larger the propeller diameter ($D$), the greater the open water efficiency ($\eta_0$).

   The minimum required equivalent blade section maximum thickness-to-chord ratio ($(t^*/c)_{min}^{75R}$), computed in
variation 3, is substantially smaller than the one computed for variation 4. As pointed out in Reference [2], the empirical relation, expressed by equation (4.9) and derived from equation (70.x) [Ref. 46: p. 620], does not take into account the effects of centrifugal loading. These effects include, specifically, the direct stresses imposed by the inertia load of the blade and the bending moments which result from rake and skew of the blade. Therefore, the algorithm developed in Chapter VI should, and does, produce a larger value for \( (t^*/c) \cdot 0.75R \).

A final observation on the results concerns the values of the open water efficiency. The "optimum" open water efficiency \( (\eta_o) \) achieved by Triantafyllou is lower than those achieved in variations 1 and 2. A possible reason for this might be the neglection of the term "dRe/dJ" in Triantafyllou's formulation of the analytical expressions [Ref. 21: p. 71] that he used in his analysis. The difference in the open water efficiencies subsequently accounts for the differences in the propeller revolution rate \( (N_p) \) and the delivered torque \( (Q_s) \) when the relation in equation (3.3) is considered.
### TABLE IV

**Design Case No. 1--Results**

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<th>GROUP</th>
<th>ITEM</th>
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VIII. DESIGN CASE NO. 2--PROGRAMMING AND COMPARISONS

A. INTRODUCTION

In this chapter, COPES/CONMIN is used in the solution of propeller selection problems which use the "power" approach. First, the power approach to the propeller selection problem is formulated. Then, a review of a previous author's solution to this problem is presented. Four variations to this propeller selection problem are solved by COPES/CONMIN. The chapter is completed with a presentation and discussion of the results from the four variations.

B. POWER APPROACH FORMULATION

1. Design Vector $\bar{X}$

As previously pointed out at the conclusion of Chapter III, Design Case No. 2 constitutes a propeller selection problem which is solved by the power approach. In this approach, the delivered torque ($Q_s$) and the propeller revolution rate ($N_p$) are specified by the designer. From the viewpoint of optimization, the quantities $Q_s$ and $N_p$ become pre-assigned parameters. This reduces the design vector $\bar{X}$ (see Figure (4.1)) to:

$$\bar{X} = \begin{pmatrix} P_E \\ V \\ D \\ P/D \\ A_E/A_O \\ (t^*/c) .75R \end{pmatrix}$$ (8.1)
Having specified $Q_S$ and $N_p$, all of the design variables, as listed in equation (8.1), are not independent. Reckoning equations (3.3), (3.11) and (3.13), the following relationship results:

$$
P_E = \frac{(1-t_d)}{(1-w_t)} \cdot n_R \cdot \frac{J K_T}{2\pi K_Q} \cdot \frac{2\pi Q_S}{550} \cdot \frac{N_p}{60} \tag{8.2}
$$

Rearranging terms, this equation becomes:

$$
\frac{P_E}{V} = \frac{(1-t_d)}{(1-w_t)} \cdot n_R \cdot \frac{(1-w_t)}{n_p D} \cdot \frac{K_T}{K_Q} \cdot \frac{Q_S}{550} \cdot \frac{N_p}{60} \tag{8.3}
$$

Considering the relations for $K_T$ and $K_Q$ in equation (3.17), then both $P_E$ and $V$ are not independent design variables. One must be selected as independent, while the other becomes dependent on the one selected.

For this study, $V$ is selected as the independent design variable. This choice will reduce the design vector $\bar{X}$ for propeller selection problems using the power approach to the following:

$$
\bar{X} = \begin{bmatrix}
V \\
D \\
P/D \\
\frac{A_e/A_Q}{(c/c)^.75R}
\end{bmatrix} \tag{8.4}
$$

Finally, equation (3.8) implies an alternative definition of $\bar{X}$ as given in equation (8.4). The design vector for
Design Case No. 2 propeller selection problems is, therefore, defined as:

\[
\bar{X}_2 = \begin{bmatrix}
V \\
J \\
P/D \\
A_E/A_O \\
(t^*/c) .75R
\end{bmatrix}
\] (8.5)

2. Powering Constraint

Having determined the design vector \(\bar{X}_2\), a final restriction to the general propeller selection problem, as stated by equation (4.24), remains for consideration. This restriction constitutes the remaining constraint \(G_{12}(\bar{X})\) mentioned in Chapter IV.

Simply stated, the selected propeller, as defined by \(X_2\), must absorb at least all of the power delivered to it \((P_D)\) which is specified in terms of \(Q_S\) and \(N_p\). Using equation (3.3), the power absorbed by the propeller can be specified in terms of delivered horsepower \((P_D)\) as:

\[
(P_D)_{\text{absorb}} = \frac{2\pi Q_p N_p}{550} \cdot \frac{N_p}{60} \tag{8.6}
\]

From equation (3.10), it follows that:

\[
(P_D)_{\text{absorb}} = \frac{K_Q \rho n_p^2 D^5}{550} \cdot \frac{2\pi N_p}{60} \tag{8.7}
\]

But, equation (3.3) also defines the power delivered to the propeller as:
\[ P_D = \frac{2\pi Q_S}{550} \cdot \frac{N_P}{60} \]  

(8.8)

The restriction imposed by the power approach method, where \( Q_S \) and \( N_P \) are specified, can now be stated as:

\[ P_D \leq (P_D)_{\text{absorb}} \]  

(8.9)

Rearranging equation (8.9), the constraint \( G_{12}(X_2) \) follows:

\[ G_{12}(X_2) = 1 - \frac{(P_D)_{\text{absorb}}}{P_D} \leq 0 \]  

(8.10)

Further simplification of equation (8.10) gives:

\[ G_{12}(X_2) = 1 - \frac{Q_p}{Q_S} \leq 0 \]  

(8.11)

With the design vector \( X_2 \) and \( G_{12}(X_2) \) defined, the propeller selection problem represented by Design Case No. 2 can be stated under one equation as:

\[
\begin{align*}
\text{Minimize: } & F(X_2) = \text{OBJ}_{1,2} \\
\text{Subject to: } & G_j(X_2) \leq 0 \quad j = 1, \ldots, 12 \\
& X_{2i}^{\text{lower}} \leq X_{2i} \leq X_{2i}^{\text{upper}} \quad i = 1, \ldots, 5
\end{align*}
\]  

(8.12)

C. PREVIOUS SOLUTIONS

Markussen [Ref. 4] considered a propeller selection problem represented by Design Case No. 2. In his example problem,
the following parameters were specified:

1) Temp = 18 (°C) = 64.4 (°F)
2) \( P_{\text{watvap}} = 0.0206411 \text{ (bars)} = 0.29943921 \text{ (psia)} \)
3) \( P_{\text{atm}} = 1.01312856 \text{ (bars)} = 14.6974 \text{ (psia)} \)
4) noscrw = 1
5) \( h_{\text{cl}} = 6.7 \text{ (meters)} = 21.9827 \text{ (ft)} \)
6) \( Z = 6 \)
7) \( P_D = 18.9 \text{ (MegaWatts)} = 25344.9 \text{ (hp)} \)
8) \( N_F = 110 \text{ (rpm)} \)
9) \( V_A = 15.65 \text{ (knots)} \)

For his analysis, the design vector contained three variables and was specified as:

\[
\begin{align*}
\bar{x}M &= \begin{bmatrix} J \\ P/D \\ A_E/A_O \end{bmatrix} \\
A \text{ restriction for the minimum required expanded area ratio } \\
(A_E/A_O)_{\text{min}}, \text{ given by equation (4.3), was also considered.} \\
\text{This imposed a constraint given by equation (4.4).} \\
\text{Using an iterative scheme [Ref. 4: p. 110] to solve three equations in three unknowns, Markussen maximized the open water efficiency } (\eta_O) \text{ to obtain the following results:} \\
J &= 0.61095 \\
P/D &= 0.864380 \\
A_E/A_O &= 36.1861/40.6123 \text{ (m}^2/\text{m}^2) \\
\end{align*}
\]
For future comparisons, equations (3.8) and (3.3) give:

\[ D = 7.19091 \text{ (meters)} = 23.593375 \text{ (ft)} \]

\[ Q_S = 1210130.0 \text{ (ft-lbf)} \]

Markussen's results are summarized in Table (V).

D. SOLUTIONS BY COPES/CONMIN

The propeller selection problem, as stated by equation (8.12), is now solved by COPES/CONMIN. Four solution variations are considered.

The first and second variations attempt to reproduce the solution given by Markussen. The design vector \( \bar{X}_M \) (NDV = 3) is used in both cases. One variation uses SUBROUTINE STRCNA to evaluate the constraint \( G_{12}(\bar{X}_M) \) given by equation (4.8). The other uses SUBROUTINE STRCNK to determine \( G_{12}(\bar{X}_M) \).

The remaining two variations will solve the propeller selection problem using the design vector \( \bar{X}_2 \) (NDV = 5) defined in equation (8.5). Again, one variation uses SUBROUTINE STRCNA; the other, SUBROUTINE STRCNK.

In all variations, the following parameters are used:

1) \( \text{Temp} = 64.4 \text{ (°F)} \)
2) \( \rho = 1.9892 \text{ (lbf-sec}^2/\text{ft}^4) \)
3) \( v = 1.1900 \times 10^{-5} \text{ (ft}^2/\text{sec)} \)
4) \( p_{\text{watvap}} = .2994 \text{ (psia)} \)
5) \( p_{atm} = 14.697 \) (psia)
6) \( wt = .22 \)
7) \( td = .19 \)
8) \( \eta_R = 1.025 \)
9) \( noscrw = 1 \)
10) \( h_{cf} = 21.9827 \) (ft)
11) \( D_{lim} = 30.0 \) (ft)
12) \( z = 6 \)
13) \( promat = 5 \) (stainless steel; see Table (II))
14) \( Q_S = 1210130 \) (ft-lbf)
15) \( N_p = 110 \) (rpm)

All of the above are initialized in the input phase (ICALC = 1) of each SUBROUTINE ANALIZ pertaining to each variation.

The constraint \( G_{12}(\overline{x}_2) \) or \( G_{12}(\overline{x}M) \) is evaluated by SUBROUTINE BLPOW2 which appears in the execution section of each SUBROUTINE ANALIZ.

1. **Variation 1**
   a. Programming Details

   Since this variation uses the design vector \( \overline{x}M \), the following design variables of \( \overline{x}_2 \) become parameters and are specified in the input section of SUBROUTINE ANALIZ (ICALC = 1). The ship's speed \( (V) \) is specified as:

   \[
   V = \frac{V_A}{(1-wt)}
   \]

   \[
   = \frac{15.65}{(1 - .22)}
   \]

   \[
   = 20.0641 \text{ (knots)}
   \]
Markussen elected to use the standard Wageningen blade section maximum thickness-to-chord ratios. Since the equivalent t/c is given as a function of Z and \( \frac{A_E}{A_O} \) (see equation (3.21)), then \((t*/c)_{.75R}\) is calculated during each analysis (ICALC = 2) by the following relation:

\[(t*/c)_{.75R} = (t/c)_{.75R}\]

For constraints, the following are used:

\[G_j(XT) \leq 0 \quad j = 1, \ldots, 8, 10, 12\]

Only ten of twelve constraints are considered (NCON = 10). Constraints \(G_9(XM)\) and \(G_{11}(XM)\) are redundant since no limit on the propeller diameter \(D_{lim}\) appears as a parameter in Markussen's formulation and \((t*/c)_{.75R}\) was taken to be the Wageningen standard.

The upper \((XM_i^{upper})\) and lower \((XM_i^{lower})\) limits on the design variables \(J\), \(P/D\) and \(A_E/A_O\) are set to be:

\[
.01 \leq J \leq 1.1 \\
.4 \leq P/D \leq 1.4 \\
.4 \leq A_E/A_O \leq 1.1
\]

These upper and lower limits are specified in the COPES control card deck on card image F under respective fields VUB and VIB. The initial value for each design variable \((XM_i)\) is

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also assigned on card image F under the field labeled X.
The first list of card images in Appendix G lists all of the COPES control cards used for this variation and variation 2. These cards also specify the locations of the design variables in the common block GLOBCM (see Table (III)) as well as the locations of the constraints and their boundaries. Further details on the COPES control card requirements and the format of each card are contained in Reference [7].

An examination of SUBROUTINE ANALIZ for this variation, found in Appendix F, shows the calling statement made to SUBROUTINE STRCNA.

b. Results

The output from the optimization/analysis, performed by COPES/CONMIN, is listed first in Appendix H. Results for this variation of the propeller selection problem are tabulated in Table (V).

2. Variation 2

a. Programming Details

Everything discussed above for the first variation applies here with one exception. An examination of SUBROUTINE ANALIZ for the second variation, found in Appendix F, shows the calling statement made to SUBROUTINE STRCNE instead of SUBROUTINE STRCNA.

b. Results

The output from the optimization/analysis, performed by COPES/CONMIN, is listed second in Appendix H.
Results for this variation of the propeller selection problem are tabulated in Table (V).

3. Variation 3
   a. Programming Details

   This variation uses the design vector $\overline{x}_2$. For constraints, the following are used:

   $$ G_j(\overline{x}_2) \leq 0 \quad j = 1, \ldots, 12 $$

   All twelve constraints are evaluated ($NCON = 12$).

   The upper ($x_{2i}^{upper}$) and lower ($x_{2i}^{lower}$) limits on the design variables $V$, $P/D$, $A_{E/A_O}$, $(t^*/c) .75R$, and $J$ are set as:

   $$ 10.0 \leq V \leq 100.0 \text{ (ft/sec)} $$
   $$ .4 \leq P/D \leq 1.4 $$
   $$ .4 \leq A_{E/A_O} \leq 1.1 $$
   $$ .003 \leq (t^*/c) .75R \leq .50 $$
   $$ .01 \leq J \leq 1.1 $$

   These upper and lower limits are specified in the COPES control card deck on card image F under respective fields VUB and VLB. The initial value for each design variable ($x_{2i}$) is also assigned on card image F under the field labeled X.

   The second list of card images in Appendix G lists all of the COPES control cards used for this variation and variation 4. These cards also specify the locations of the design variables.
in the common block GLOBCM (see Table (III)) as well as the locations of the constraints and their boundaries. Further details on the COPES control card requirements and the format of each card are contained in Reference [7].

An examination of SUBROUTINE ANALIZ for this variation, found in Appendix F, shows the calling statement made to SUBROUTINE STRCNA.

b. Results
The output from the optimization/analysis, performed by COPES/CONMIN, is listed third in Appendix H. Results for this variation of the propeller selection problem are tabulated in Table (V).

4. Variation 4
a. Programming Details
Everything discussed above for the third variation applies here with one exception. An examination of SUBROUTINE ANALIZ for the fourth variation, found in Appendix F, shows the calling statement made to SUBROUTINE STRCNK instead of SUBROUTINE STRCNA.

b. Results
The output from the optimization/analysis, performed by COPES/CONMIN, is listed last in Appendix H. Results for this variation of the propeller selection problem are tabulated in Table (V).

E. DISCUSSION
The results achieved in variations 1 and 2 compare extremely well to the solution obtained by Markussen. As
pointed out in the discussion in Chapter VII, variations 1 and 2 are expected to give the same results for the vector \( \overline{X} \). Obviously, the values obtained for \( J \) and \( P/D \), as well as those for \( D \), and \( Rn^{*} \) are very close to the values generated in Markussen's example. However, the values for \( AE/AO \) are somewhat different. It is interesting to note that the value obtained in variations 1 and 2 (and, for that matter, variations 3 and 4) is, essentially, the limiting value for \( AE/AO \), as given in Table (I), for \( Z = 6 \). Markussen's value for \( AE/AO \) (i.e., \( .891012 \)) exceeds the limit (i.e., \( .80 \)) in this table.

As pointed out at the end of Chapter VII, the minimum required blade section maximum thickness-to-chord ratio \( (t^*/c)_{.75R \text{ min}} \), computed in variations 1 and 3, is substantially smaller than the one computed for variations 2 and 4. Again, the same explanation applies here as well.

The results of variations 3 and 4 differ somewhat from Markussen's results. The reason for this is simply that \( V_A \) (or \( V \)) has not been specified as a parameter. Consequently, a higher value for the advance ratio (\( J \)), which corresponds to a higher open water efficiency (\( \eta_O \)), has been found in the optimization search. This result can be interpreted in the following way. Given:

1) a six-bladed Wageningen propeller (\( Z = 6 \)) which is made out of stainless steel (promat = 5);

2) a power train delivering 25344.9 (hp) at a rate of 110 (rpm);
3) a hull with a wake fraction (wt) equal to .22, a thrust deduction (td) equal to .19 and a shaft centerline depth ($h_{cz}$) of 21.98 (ft), then, the selected propeller, as defined by $X_2$, can drive this hull at a maximum speed of $V$ when the hull has a maximum resistance given by $P_E$. 
**TABLE V**

**Design Case No. 2—Results**

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IX. DESIGN CASE NO. 3--PROGRAMMING AND COMPARISONS

A. INTRODUCTION

In this chapter, COPES/CONMIN is used in the solution of a propeller selection problem where "matching" is desired. First, the "matching" approach to the propeller selection problem is formulated. Then, a review of a previous author's solution is presented. One variation to this propeller selection problem is solved by COPES/CONMIN. The chapter is completed with a presentation and discussion of the results.

B. "MATCHING" FORMULATION

1. Design Vector $\overline{X}^3$

Design Case No. 3, the final powering problem considered in this study, constitutes a propeller selection problem solved by the "matching" approach. In this approach, the hull's effective horsepower ($P_E$) and speed ($V$), the delivered torque ($Q_S$) and the propeller revolution rate ($N_p$) are specified by the designer. This reduces the design vector $\overline{X}$ (see Figure (4.1)) to:

$$\overline{X} = \begin{pmatrix} D \\ P/D \\ \frac{A_E}{A_0} \\ (t^*/c) .75R \end{pmatrix}$$  \hspace{1cm} (9.1)

For this study, the design vector $\overline{X}$ is reduced further by eliminating the propeller diameter ($D$) as a design variable.
That is, D will also be specified by the designer so that the design vector for Design Case No. 3 is defined as:

\[
\mathbf{X}_3 = \begin{cases} 
P/D \\ 
A_e/A_o \\ 
(t^*/c) .75R 
\end{cases} \tag{9.2}
\]

2. **Powering Constraint(s)**

Having determined the design vector \( \mathbf{X}_3 \), a final restriction to the general propeller selection problem, as stated by equation (4.24), remains for consideration. This restriction constitutes the remaining constraint \( G_{12}(\mathbf{X}) \) mentioned in Chapter IV as well as an additional constraint.

In the "matching" problem, the selected propeller, as defined by \( \mathbf{X}_3 \), must satisfy two conditions. First, it must develop, as a minimum, the effective horsepower \( (P_E) \) as imposed by the design specification. Citing the formulation previously derived in Chapter VII, this condition can be stated as:

\[
P_E \leq (P_E)^{\text{dev}} \tag{9.3}
\]

The constraint \( G_{12}(\mathbf{X}_3) \) follows accordingly as:

\[
G_{12}(\mathbf{X}_3) = 1 - \frac{(P_E)^{\text{dev}}}{P_E} \leq 0 \tag{9.4}
\]

For the second condition, the selected propeller can only absorb, as a maximum, the delivered power \( (P_D) \) as
specified by the designer. The formulation is the same as that in Chapter VIII except that the inequality signs are reversed. The condition is stated as:

\[(P_D)_{\text{absorb}} \leq P_D\]  \hspace{1cm} (9.5)

In defining a constraint \(G_{13}(X3)\), another location, say location 24, in the GLOBCM block (see Table (III)) would be assigned. But, considering the fact that constraint \(G_9(X)\) will not be used because the propeller diameter \((D)\) is specified, there is no reason why \(G_9(X3)\) cannot be redefined, for this Design Case only, as:

\[G_9(X3) = \frac{(P_D)_{\text{absorb}}}{P_D} - 1 \leq 0\]  \hspace{1cm} (9.6)

Further simplification of equation (9.6) gives:

\[G_9(X3) = \frac{Q_P}{Q_S} - 1 \leq 0\]  \hspace{1cm} (9.7)

In reality, the constraints just defined should be equality constraints. The word "match" does infer equality in some sense. However, as previously stated in Chapter II, the version of COPES/CONMIN used in this study does not directly handle equality constraints. But, since CONMIN attempts to minimize constraints in the optimization search, it will be assumed that a "match" can be achieved.
With the design vector $\mathbf{x}_3$ and the constraints $G_{12}(\mathbf{x}_3)$ and $G_9(\mathbf{x}_3)$ defined, the propeller selection problem represented by Design Case No. 3 can now be stated under one equation as:

Minimize: $F(\mathbf{x}_3) = \text{OBJ}_3$

Subject to: $G_j(\mathbf{x}_3) \leq 0$ \hspace{1cm} j = 1, \ldots, 12 \hspace{1cm} (9.8)

$x_{3_i}^{\text{lower}} \leq x_i \leq x_{3_i}^{\text{upper}} \hspace{1cm} i = 1, \ldots, 3$

C. PREVIOUS SOLUTIONS

The propeller selection problem considered by Vassilopoulos [Ref. 18] actually represents a propeller "design" problem using the "power" approach. The example problem which he elected to solve is taken from that posed by the International Towing Tank Conference (ITTC) Propeller Committee. This problem is concerned with the determination of propeller thrust ($T$), diameter ($D$) and speed of advance ($V_A$) (or ship speed ($V$)) for a single-screw cargo ship where:

1) power available to the propeller (i.e., $P_D$) is 30,000 (hp)

2) $Z = 6$

3) $N = 105--110$ (rpm)

4) $D_{\text{lim}} = 23$ (ft)

5) $h_{\text{cf}} = 19$ (ft)

The variation of ship speed ($V$) and of hull effective power ($P_{\text{e}}$), thrust deduction factor ($\text{td}$) and the wake fraction ($\text{wt}$) is also given [Ref. 18: p. 20].
The results from Vassilopoulos' propeller design exercise produced a propeller that is "matched" at the following values:

1) $P_E = 21292.6$ (hp)
2) $V = 24.24$ (knots)
3) $Q_S = 1500606.75$ (ft-lbf)
4) $N_P = 105$ (rpm)
5) $P_D = 30000.0$ (hp)

His propeller "design" was based upon the following specified parameters:

1) $\text{Temp} = 59$ (°F)
2) $\rho = 1.9905$ (lbf·sec$^2$/ft$^4$)
3) $P_{\text{watvap}} = .247$ (psia)
4) $\omega = .22$
5) $td = .1725$
6) $\text{noscwr} = 1$
7) $h_{cL} = 19.0$ (ft)
8) $Z = 6$
9) promat = 5 (stainless steel, see Table (II))
10) $D = 22.0$ (ft)
11) $N_P = 105$ (rpm)
12) $P_D = 30000.0$ (hp)

Using an optimization scheme incorporated in his MVAPDP computer program, Vassilopoulos maximized the open water efficiency ($\eta_o$) and designed a propeller with the following characteristics:

1) $J = .852$
2) $K_T = .242$
3) \( K_Q = .0478 \)
4) \( n_o = .691 \)
5) \( A_E/A_O = .767 \)
6) \( \text{bldwt} = 7617.2 \text{ (lbf)} \)

By utilizing both the lifting line and lifting surface methods in his design procedure, Vassilopoulos' MVAPDP program evolved a "constant stress" propeller blade. Consequently, the values for \((t*/c)\) and \(P/D\) varied non-linearly along the propeller radius \((R)\). According to Vassilopoulos, this resulted in a minimum weight propeller. The values for \(P/D\) and \((t*/c)\) are listed in Tables (8) and (10) of his paper. From these values, \((t*/c)\) \(0.75R\) is approximately 0.040.

While the propeller represented by Vassilopoulos' design is different, in many aspects (rake, skew, blade section aerfoil shape, etc.), from the Wageningen B-Screw Series propeller, it does represent a minimum weight propeller that has been "matched" to specific design values. Appropriate results are summarized in Table (VI).

D. SOLUTIONS BY COPES/CONMIN

The propeller selection problem, as stated by equation (9.8), is now solved by COPES/CONMIN. One solution variation is considered. The following parameters are used:

1) \( \text{Temp} = 59 \text{ (°F)} \)
2) \( \rho = 1.9905 \text{ (lbf-sec}^2\text{/ft}^4) \)
3) \( v = 1.2817 \times 10^{-5} \text{ (ft}^2/\text{sec}) \)
4) \( P_{watvap} = .247 \text{ (psia)} \)
5) $P_{atm} = 14.7$ (psia)
6) $wt = .22$
7) $\eta_R = 1.025$
8) noscrw = 1
9) $h_{cl} = 19.0$ (ft)
10) $Z = 6$
11) promat = 5 (stainless steel, see Table (II))
12) $D = 22.0$ (ft)

Two problems are examined. Problem 1 specifies the following additional parameters:

1) $td = .1725$
2) $P_E = 21292.6$ (hp)
3) $V = 24.24$ (knots)
4) $Q_S = 1500606.75$ (ft-lbf)
5) $N_p = 105$ (rpm)

Problem 2 specifies the same parameters as:

1) $td = .171$
2) $P_E = 17630.0$ (hp)
3) $V = 23.0$ (knots)
4) $Q_S = 1500606.75$ (ft-lbf)
5) $N_p = 105$ (rpm)

All of the above are initialized in the input section (ICALC = 1) of similar versions of SUBROUTINE ANALIZ. Therefore, only one version is included in Appendix I.

The constraints for $G_9(X^3)$ and $G_{12}(X^3)$ are evaluated by SUBROUTINE BLPOW3 which appears in the execution section of
SUBROUTINE ANALIZ. Also, note that SUBROUTINE DICNUA has been deleted from the execution section, while SUBROUTINE WGCAL has been added.

1. Programming Details

All twelve constraints are evaluated (NCON = 12). The upper ($X_{3\text{upper}}$) and lower ($X_{3\text{lower}}$) limits on the design variables P/D, $A_E/A_O$ and $(t*/c)_{75R}$ are set to be:

\[
\begin{align*}
0.4 & \leq P/D \leq 1.4 \\
0.4 & \leq A_E/A_O \leq 1.1 \\
0.003 & \leq (t*/c)_{75R} \leq 0.50
\end{align*}
\]

These upper and lower limits are specified in the COPES control card deck on card image F under respective fields VUB and VLB. The initial value for each design variable ($X_{3i}$) is also assigned on card image F under the field labeled X. The list of card images in Appendix J lists all of the COPES control cards used for both problems. These cards also specify the locations of the design variables in the common block GLOBCM (see Table (III)) as well as the locations of the constraints and their boundaries. Further details on the COPES control card requirements and the format of each card are contained in Reference [7].

2. Results

The outputs from the optimization/analysis, performed by COPES/CONMIN, are listed in Appendix K. Results of both problems are tabulated in Table (VI).
E. DISCUSSION

Table (VI) presents the results of problems 1 and 2 along with relevant information from Vassilopoulos' "design". Problem 1 attempted to "match" a Wageningen propeller at the design point found by Vassilopoulos. The first COPES/CONMIN printout in Appendix K indicates that the "match" was achieved at $P_E$ equal to 21,168.1 (hp) and $P_D$ equal to 28,150.0 (hp) (or, $Q_S = 1500607$ (ft-lbf) and $N_p = 105$ (rpm)). These values are judged to be close enough to the "Given" values in Table (VI).

It is apparent that the Wageningen propeller does not require all of the 30,000 (hp) of delivered horsepower. The propeller characteristics (i.e., $J$, $K_T$, $K_Q$ and $\eta_o$) for problem 1 compare very well to Vassilopoulos' values. The expanded area ratios ($A_E/A_O$) are, also, very similar. Of course, the obvious difference is the blade weight (bldwt). The Wageningen propeller blade is over five thousand pounds heavier. Does this make sense for a minimum blade weight?

The answer is yes. All one has to do is consider the values of $(t^*/c)$ for problem 1 and Vassilopoulos' design. Vassilopoulos' "constant stress" blade was designed to "absorb" stress up to the allowable design limit of 5,400 (psi) (for stainless steel) all along the entire propeller radius ($R$). Table (12) in Reference [18] gives further details. The Wageningen propeller blade, however, represents an "older" type of blade which was designed with a linear blade section maximum thickness ($t^*$).
distribution. Consequently, it was "overdesigned" for strength beyond the 3/10--4/10 radius (i.e., .3R--.4R) and contains excess material. A heavier blade, therefore, results. Note, also, that the optimizer did not drive the value of \((t^*/c)_{.75R}\) to the minimum acceptable value, \((t^*/c)_{.75R_{min}}\). 

The results of problem 2 show the effect on blade weight (bldwt) for a Wageningen propeller when the hull's powering requirements (i.e., \(P_E\) at \(V\)) have been reduced. The weight reduction of 2000 pounds is significant. The complete results are listed in the second COPES/CONMIN printout in Appendix K.
TABLE VI

Design Case No. 3--Results

<table>
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<th>GROUP</th>
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<th>VASSILOPOULOS 1</th>
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*P/D varies with R
CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

The general purpose non-linear optimizer/synthesizer COPES/CONMIN has been successfully applied to three typical preliminary ship design propeller selection problems in which the Wageningen B-Screw Series is used. The formulation and programming of each required analysis code (i.e., SUBROUTINE ANALIZ) have been made as general as possible to allow the designer a broad variety of solution options for solving propeller selection problems which can be classified under any of the three Design Cases that were considered. The analysis codes have been "modularized" to the extent that methodical series data from other propeller series, which are available in the polynomial expression format of the B-Screw Series, can be easily adapted for powering analysis utilizing design optimization methods.

Further flexibility in the solution to the propeller selection problem has been achieved by using COPES/CONMIN as the optimizer/synthesizer. The designer has now been afforded the additional capability of specifying the design variables, the objective functions and the constraints of his choice. By solving propeller selection problems in the way presented in this thesis, repetitive problem formulation and coding have been eliminated.

There are other advantages to solving propeller selection problems specifically with COPES/CONMIN which have not been
directly addressed in this study. As stated in Chapter II, COPES/CONMIN is capable of performing optimization analyses, sensitivity studies, optimum sensitivity studies and optimization using approximation techniques. The designer, therefore, can select and perform any of these options, using the same analysis codes which have been presented in this thesis.

While the utilization of a general purpose non-linear optimizer in solving propeller selection problems allows the designer greater flexibility in the selection procedure, there is one important limitation that should be stressed at this point. This concerns the question whether or not the solution vector, determined by the optimizer, is a "global" optimum. As stated in Chapter II, COPES/CONMIN assures that, if a feasible solution vector is found, it is, at least, a "local" minimum (or maximum). This implies that, for two different initial design vectors which are specified in the COPES Control Card deck on card image F, the same optimum solution may not be determined by the optimizer. Both solutions would correspond to minimums (or maximums) of the objective function and are, therefore, correct. But, does one or the other correspond to the minimum (or maximum) of the entire vector design space, i.e., the "global" optimum? For the moment, at least, there is no definitive answer to the question.

Despite this uncertainty, progress in the field of design optimization continues to be made. Current developments [Ref. 47] will soon allow the designer to have a choice in
selecting a specific optimization algorithm from a "library" of proven optimization programs which employ the latest state-of-the-art numerical techniques. Again, using one analysis code, the designer will be able to generate any number of optimized solutions for the problem under study.

B. RECOMMENDATIONS

For future consideration, it is recommended that the automated design and trade-off capability, provided by a general purpose non-linear optimizer/synthesizer such as COPES/CONMIN, be applied to the more difficult problem of propeller design.

As pointed out in Chapter I, the use of the Wageningen B-Screw Series represents a "selection" procedure rather than a "design" process. Today, analytical propeller design procedures, utilizing lifting line and lifting surface theory, are becoming increasingly popular among propeller designers. The propeller design, which results from the utilization of these analytical methods, is, unquestionably, more efficient than the standard series propeller. However, these methods require consideration of many more design variables in the design process. This appears to be a natural application for the use of a general purpose non-linear optimizer/synthesizer.

Here, an analysis code, much larger than those which have been presented in this study, could be developed which would incorporate the lifting line/lifting surface theory.
for the determination of the propeller performance characteristics, the local cavitation numbers and also the calculation of the pressure distributions over the blade. These pressure distributions would be utilized in the strength analysis of the blade. This analysis would utilize the finite element technique on an appropriately generated mesh model of the blade. Having defined the steps for this design procedure in the analysis code, the propeller designer now "couples" his analysis to the optimizer/synthesizer for determination of the optimum design. A massive amount of computer storage would certainly be required, but this concept is feasible and, in the author's view, is worthy of future consideration.

C. A FINAL NOTE

In conclusion, this thesis has demonstrated, in effect, another interesting application of the method of design optimization. The author, in no way, wishes to leave the reader with the impression that the techniques of design optimization are the "be all--end all" for engineering analysis. Design optimization techniques are useful and powerful tools that stand to relieve the engineer of the mundane tasks of numerical calculations and subsequent graphic plotting. But, they are just tools. In the final "analysis", good engineering judgment is paramount in their application and use.
## APPENDIX A

### FORTRAN VARIABLE CROSS REFERENCE LIST

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</tr>
<tr>
<td>Q$_S$</td>
<td>QS</td>
</tr>
<tr>
<td>Rn$.75$R</td>
<td>R75R</td>
</tr>
<tr>
<td>S$_C$</td>
<td>SC</td>
</tr>
<tr>
<td>td</td>
<td>TD</td>
</tr>
<tr>
<td>Symbol</td>
<td>Fortran Variable</td>
</tr>
<tr>
<td>--------------</td>
<td>-----------------</td>
</tr>
<tr>
<td>Temp</td>
<td>TEMP</td>
</tr>
<tr>
<td>$(t^*/c)^{.75}R$</td>
<td>TC75R</td>
</tr>
<tr>
<td>$v$ (ft/sec)</td>
<td>V</td>
</tr>
<tr>
<td>$v$ (knots)</td>
<td>VK</td>
</tr>
<tr>
<td>wt</td>
<td>WT</td>
</tr>
<tr>
<td>z</td>
<td>Z</td>
</tr>
<tr>
<td>$n_o$</td>
<td>ETAO</td>
</tr>
<tr>
<td>$n_R$</td>
<td>ETARR</td>
</tr>
<tr>
<td>$\nu$</td>
<td>WATNU</td>
</tr>
<tr>
<td>$\rho$</td>
<td>WATRO</td>
</tr>
</tbody>
</table>
SUBROUTINE ELPGRP

SUBROUTINE: BLPGRP

INPUT      OUTPUT
AECVAG     DATE OF LAST REVISION: APK 83
DIA        APP0060
Z          APP0070
COMMON /TH1CD/

COMMON/AREBLO/
COMMON/CGX/
LOCATION OF BLADE CROSS-SECTIONAL AREA CENTROID WITH RESPECT TO GENERATOR LINE
(BEETE)
COMMON/CGY/
LOCATION OF BLADE CROSS-SECTIONAL AREA CENTROID WITH RESPECT TO PITCH-REFERENCE LINE (FEET)
COMMON/CRLNT/
BLADE SECTION CHORD LENGTHS (FEET)
COMMON/VALU1/
ORIGIN OF CRITICAL POINT NO. 1 ON BLADE SECTION PERIPHERY WITH RESPECT TO A SYSTEM OF AXES PARALLEL AND NORMAL TO PITCH-REFERENCE LINE WITH ORIGIN AT THE CENTROID OF THE SECTION (FEET)
COMMON/VALW1/
ABSCISSA OF CRITICAL POINT NO. 1 ON BLADE SECTION PERIPHERY WITH RESPECT TO A SYSTEM OF AXES PARALLEL AND NORMAL TO PITCH-REFERENCE LINE WITH ORIGIN AT THE CENTROID OF THE SECTION (FEET)
COMMON/VALU2/
ORIGIN OF CRITICAL POINT NO. 2 ON BLADE SECTION PERIPHERY WITH RESPECT TO A SYSTEM OF AXES PARALLEL AND NORMAL TO PITCH-REFERENCE LINE WITH ORIGIN AT THE CENTROID OF THE SECTION (FEET)
COMMON/VALW2/
ABSCISSA OF CRITICAL POINT NO. 2 ON BLADE SECTION PERIPHERY WITH RESPECT TO A SYSTEM OF
COMM/TVAL3/
AXES PARALLEL AND NORMAL TO
PITCH-REFERENCE LINE WITH ORI-
GIN AT THE CENTROID OF THE
SECTION (FEET) APP05490
ORIGINATE OF CRITICAL POINT NO. APP05530
3 ON BLADE SECTION PERIPHERY APP05360
WITH RESPECT TO A SYSTEM OF
AXES PARALLEL AND NORMAL TO
PITCH-REFERENCE LINE WITH ORI-
GIN AT THE CENTROID OF THE
SECTION (FEET) APP05570
COMM/TVAL4/
ORIGINATE OF CRITICAL POINT NO. APP06040
4 ON BLADE SECTION PERIPHERY APP06080
WITH RESPECT TO A SYSTEM OF
AXES PARALLEL AND NORMAL TO
PITCH-REFERENCE LINE WITH ORI-
GIN AT THE CENTROID OF THE
SECTION (FEET) APP06080
COMM/TVAL5/
ORIGINATE OF CRITICAL POINT NO. APP06060
4 ON BLADE SECTION PERIPHERY APP06070
WITH RESPECT TO A SYSTEM OF
AXES PARALLEL AND NORMAL TO
PITCH-REFERENCE LINE WITH ORI-
GIN AT THE CENTROID OF THE
SECTION (FEET) APP06080
COMM/TVAL6/
ORIGINATE OF CRITICAL POINT NO. APP06090
4 ON BLADE SECTION PERIPHERY APP06070
WITH RESPECT TO A SYSTEM OF
AXES PARALLEL AND NORMAL TO
PITCH-REFERENCE LINE WITH ORI-
GIN AT THE CENTROID OF THE
SECTION (FEET) APP06080
REAL*4 ETA0, WEIGHT*, AEQVAK, DIA.N, PE, PD1 WD, QS, TC75K, V,
1 APP06920
FJCNL, RJCNU, R75KCL, R75KLU, AEACL, AEALCU, IC15L, TC15L,
APP05520
FCHBL, DIACNL, AEACLV, TCSTAS,
APP05440
VK, IE, WTZ, WATRO, WATN, TEP, NOSCRW, HCL, PATH,
APP05530
PMAT, PGMAT, DIALIM, ETAKK,
Determine chord lengths along blade radius using Table 1, Ref 2

IF NOT(12.60 ≤ 1) GO TO 1
CR1[1] = 1.532 * AEDVAO * DIA1 / 2
GO TO 3
1 CONTINUE
IF NOT(12.60 ≤ 2) GO TO 2
CR1[2] = 1.5694 * AEDVAO * DIA1 / 2
GO TO 3
2 CONTINUE
IF NOT(12.60 ≤ 3) GO TO 3
CR1[3] = 1.5894 * AEDVAO * DIA1 / 2
GO TO 3
3 CONTINUE
IF (.NOT. (I.EQ.6)) GO TO 4
CR(1) = 1.385*AEDVAM*DIA/2
GO TO 5
4 CONTINUE
CR(1) = (1.6180*AEDVAM*DIA)/2
5 CONTINUE
IF (.NOT. (I.EQ.3)) GO TO 6
CR(2) = (1.6330*AEDVAM*DIA)/2
CR(3) = (1.8320*AEDVAM*DIA)/2
CR(4) = (2.0000*AEDVAM*DIA)/2
CR(5) = (2.1200*AEDVAM*DIA)/2
CR(6) = (2.1860*AEDVAM*DIA)/2
CR(7) = (2.1680*AEDVAM*DIA)/2
CR(8) = (2.1270*AEDVAM*DIA)/2
CR(9) = (1.6570*AEDVAM*DIA)/2
CR(10) = (0.0000*AEDVAM*DIA)/2
GO TO 7
6 CONTINUE
CR(2) = (1.6620*AEDVAM*DIA)/2
CR(3) = (1.8820*AEDVAM*DIA)/2
CR(4) = (2.0500*AEDVAM*DIA)/2
CR(5) = (2.1880*AEDVAM*DIA)/2
CR(6) = (2.1440*AEDVAM*DIA)/2
CR(7) = (2.1400*AEDVAM*DIA)/2
CR(8) = (1.9700*AEDVAM*DIA)/2
CR(9) = (1.9500*AEDVAM*DIA)/2
CR(10) = (0.0000*AEDVAM*DIA)/2
7 CONTINUE
CALCULATE POSITION OF GENERATOR LINE (1.EQ. AR(I)) AND POSITION OF POINT (APP01750)
MAXIMUM GEAR SECTION THICKNESS (I.E., ER(I)) USING TABLE (1), REFER
IF (.NOT. (I.EQ.3)) GO TO 8
AR(I) = (0.617*CR(I))
BR(I) = (0.350*CR(I))
GO TO 12
8 CONTINUE
IF (.NOT. (I.EQ.4)) GO TO 9
AR(I) = (0.61832*CR(I))
BR(I) = (0.350*CR(I))
GO TO 12
9 CONTINUE
IF (.NOT. (I.EQ.5)) GO TO 10
AR(I) = (0.61832*CR(I))
BR(I) = (0.350*CR(I))
GO TO 12
10 CONTINUE
DETERMINE "FORWARD" (P=0, TC P=+1) AND "AFT" (P=0 TO P=-1) INTEGRATION INTERVALS WITH RESPECT TO PITCH-REFERENCE LINE FOR EACH BLADE SECTION ALONG PROPELLER BLADE RADIUS USING FIGURE 1 AND TABLE (1), REF 2.

DO 15 I=1,1C
   PLF(I)=DR(I)
   PLA(I)=CR(I)-PLF(I)
15 CONTINUE

INITIALIZE MAXIMUM BLADE SECTION THICKNESS ALONG PROPELLER BLADE RADIUS.

TR(1)=T1XR
TR(2)=T2CR
TR(3)=T3CR
TR(4)=T4CR
TR(5)=T5CR
TR(6)=T6CR
TR(7)=T7CR
TR(8)=T8CR
TR(9)=T9CR
TR(10)=T10GF

INITIALIZE VALUES FOR "VL" & "V2" (P=0 TO P=+1) AND "VL" & "V2" (P=0 TO P=-1) IN RELATIONS (2) AND (3), REF 2, USING VALUES FROM TABLE (2), REF 2.

... BEGIN AT R=0.18K FOR PROPELLERS WITH 3 OR 7 BLADES.

IF(NCF .EQ. 3.0) OR (L.EQ.7.0) JUG TC 16

VIF(1:1)=0.0000
VIF(1:2)=0.0063
VIF(1:3)=0.0336
VIF(1:4)=0.0556
VIF(1:5)=0.0851
VIF(1:6)=0.1238
VIF(1:7)=0.1761
VIF(1:8)=0.2092
VIF(1:9)=0.2460
VIF(1:10)=0.2547
VIF(1:11)=0.3678
VIF(1:12)=0.4000
VIA(1:1)=0.0232
VIA(1:2)=0.0722
VIA(1:3)=0.1028
VIA(1:4)=0.1332
GO TO 17

... OR BEGIN AT K = .167 R FOR PROPPELLERS WITH 4, 5, OR 6 BLADES
CALCULATE BLADE SECTION PROPERTIES ALONG PROPPELLER BLADE RADIUS

R
1.17R OR .18R
.2R
.3R
.4R
.5R
.6R
.7R
.8R
.9R
1.00R

DO 52 IR=1,10

*** INITIALIZE SUMMATION VARIABLES TO ZERO FOR EACH ITERATION ***

SLPAA=C.0
SUPAA=0.0
SMAA=0.0
SKAY2A=0.0
SUPAF=C.0
SUPAY=0.0
SUPAXF=0.0
SUPAYF=0.0
SMAZ2F=0.0
DLPFSM=0.0

*** BEGIN WITH "AFT" PORTION (P=0 TO P=-1) OF BLADE SECTION AS DEPICTED IN FIGURE (11), REF 2 ***

DC 11 I=1,5
1
1

IP1=IP2

YFACE(I1) = (VIA(I1,IR,1) + (TR(IR)-0.1*TR(IR)))
YEACK(I1) = (VIA(I1,IR,1) + V2A(IR,1)) + (TR(IR)-0.1*TR(IR))

H(I1) = YBACK(I1) + YFACE(I1) + 2.0

YFACE(IP1) = (VIA(IP1,IR,1) + V2A(IR,1)) + (TR(IR)-0.1*TR(IR))
YEACK(IP1) = (VIA(IP1,IR,1) + V2A(IR,1)) + (TR(IR)-0.1*TR(IR))

H(IP1) = YBACK(IP1) + YFACE(IP1)

Y(IP1) = YBACK(IP1) + YFACE(IP1) + 2.0

IF1=IF1+1 OR (1=0) GO TO 18

DELPA(I1) = (PLA(IR)/10.0) + 2.0

GC TO 20
CONTINUE
IF NOT ((1.EQ.8).OR.*(1.EQ.9)) GO TO 19
DELPA(1)=PLATIR/10.01*C.5
GO TO 20
CONTINUE
DELPA(1)=(PLATIR/10.01)*1.0
CONTINUE
AA(I)=10.5*(HA(I)*HA(I))**DELPA(11)
DLPA=DLFAM*DELPA(I)
X(I)=DLPA*(DELPA(I)/2)//0
Y(I)=(Y(I)+Y(I))/2.0
SLMAX=SUMAX*(AA(I)**X(I))
SLMAX=SUMAX*(AA(I)**Y(I))
SPTMAX2=SUMAX*(AA(I)**(X(I)+Y(I)))*11
SPTAYSA=SUMAX*(AA(I)**(Y(I)+X(I)))*11
SPTAYSA=SUMAX*(AA(I)**(Y(I)+X(I)))*11
CONTINUE
CONTINUE
CONTINUE WITH "FORWARD" PORTION (P=0 TO P=+1) OF BLADE SECTION AS DEPICTED IN FIGURE (1), REF 2
DC 25 J=1,10
IF I=1+1
VFACE(I)=(VIF(I)+I)/2.0
YEACK(I)=(VIF(I)+I)/2.0
1
HF(I)=VBACK(I)-YFACE(I)
Y(I)=VBACK(I)-VFACE(I)/2.0
Y(I)=VBACK(I)-VFACE(I)/2.0
1
HF(I)=VBACK(I)-YFACE(I)
Y(I)=VBACK(I)-VFACE(I)/2.0
IF NOT ((1.EQ.1).OR.*(1.EQ.2)) GO TO 22
DELPA(1)=(PLF(I)/10.01)*1.0
GO TO 25
CONTINUE
IF NOT ((1.EQ.7).OR.*(1.EQ.8).OR.*(1.EQ.9).OR.*(1.EQ.10)))
GO TO 23
DELPA(1)=(PLF(I)/10.01)*C.5
GO TO 24
CONTINUE
DELPA(1)=(PLF(I)/10.01)*1.0
CONTINUE
A(I)=0.5*(HF(I)+HF(I))**DELPA(1)
DLPF=DLFAM*DELPA(1)
\[ \begin{align*}
X & (1) = ULPF5M - (DELPF(1)) / 2.0 \\
Y & (1) = (Y(1) + Y(1)) / 2.0 \\
SMAF & = SUMAF (1) \\
SMAV & = SUMAVF * (AF(1) * X(1)) \\
SPAXF & = SMAXF * (AF(1) * Y(1)) \\
SPAF & = SMAXF * (AF(1) * Y(1)) \\
\end{align*} \]

**CONTINUE**

**Determine blade section properties, i.e., cross-section area, and area centroid location with respect to pitch-reference line and line of maximum blade section thickness as depicted in Figure (1), Ref 2**

**AREA[I] = SLMA + SUMAF**

**IF (NOT (AREA[I] <= 0.0)) GO TO 26**

**YFRL[I] = 0.0**

**CC CONTINUE**

**GO TO 27**

**CONTINUE**

**Calculate moment of inertia with respect to neutral axis using parallel axis theorem**

**RIYNA[I] = (SUMAXF + SUMAY) - ((XMT[I] * XMT[I]) / 2) * AREA[I]**

**RIXNA[I] = (SUMAYF + SMAY) - ((YPRL[I] * YPRL[I]) / 2) * AREA[I]**

**CONTINUE**

**Determine location of "CG", i.e., neutral axes origin, with respect to pitch-reference line and generator line depicted in Figure (1), Ref 2**

**IF (NOT (XMT[I] <= 0.0)) GO TO 28**

**DA = BR (I) + ABS (XMT[I])**

**GO TO 30**

**CONTINUE**

**IF (NOT (XMT[I] <= 0.0)) GO TO 29**

**DA = BR (I) - ABS (XMT[I])**

**GO TO 30**

**CONTINUE**

**DA = BR (I)**

**GO TO 30**
42 CONTINUE
U(1,IR)=0.0
APP05410
43 CONTINUE
APP05420
44 GC TO 45
APP05430
45 CONTINUE
U(1,IR)=YBK-YCG(1,IR)
APP05440
APP05660
46 RC 1,45
APP05450
47 GC TO 48
APP05460
48 CONTINUE
U3(1,IR)=YBK-YCG(1,IR)
APP05470
49 CONTINUE
APP05480
50 GC TO 51
APP05490
51 CONTINUE
APP05500
52 CONTINUE
RETURN
APP05510
END
SUBROUTINE ELVCL(VCLBLD)

SUBROUTINE: BLEVOL

INPUT

PROPELLER DIAMETER (FEET)

OUTPUT

NO. OF PROPELLER BLADES

BLADE SECTION AREAS (FEET**2)

PROPELLER BLADE VOLUME (FEET**3)

REAL*4 ETA0, WEIGHT, AEDVAD, DIA, N, PE, R1, VC, QS, CT75K, V,

1

FECA, RJCNV, R75C, R75CU, AEAGC, AECU, CT75CL, TL75CU,

2

PCWWD, DIACN, AEADC, TCSTAS,

3

W, WT, Z, WATRC, WATNU, TEMP, NOSCRM, HCL, PATH,

4

P, ATLA, PRMAT, DIMAL, ETARK,

5

W, JCNV, R75K, KG

REAL*4 AREA(101), LENGTH, VOL2, VOL2LBD

COMMON /PLEG3M/ETA0, WEIGHT, AEDVAD, DIA, N, PE, R1, VC, QS, CT75K, V, RJCNV,

1

R75C, R75CU, AEAGC, AECU, CT75CL, TL75CU, PCWWD, DIACN, AEADC, TCSTAS,

2

COMMON /PARAM/VK, TD, WT, Z, WATRU, WATNU, TEMP, NOSCRM, HCL, PATH, PWATVA,

1

COMMON /C2/ DIAL, ETARK, AEACMN, CT75MN, SC

DETERMINE BLADE VOLUME BY SIMPSON INTEGRATION SCHEME OF BLADE

CROSS-SECTIONAL AREAS FROM 2/10 RADIUS COWARD TO TIP

VOL=(((C2/2.01)*0.11/3.01)*AREA(2)+(4.0*AREA(3))+(2.0*AREA(4))+(4.0*AREA(5))+(2.0*AREA(6))+(4.0*AREA(7))+(2.0*AREA(8))+(4.0*AREA(9)))+AREA(10))

DETERMINE BLADE VOLUME FROM 2/10 RADIUS COWARD TO R=.18 R FOR 3 & 7 BLADE PROPPELLERS OR R=.18 R FOR 4, 5, & 6 BLADE PROPPELLERS USING SIMPLE TRAPEZOIDAL INTEGRATION SCHEME

IF (.NOT.(Z.EQ.3.O)) GO TO 1

IF (.NOT.(Z.EQ.4.O)) GO TO 2

1 CONTINUE

IF (.NOT.(Z.EQ.5.O)) GO TO 3

APPENDICISE
GO TO 5
3 CONTINUE
   IF (.NOT. (Z.EQ.6.0)) GO TO 4
   WICT = (DIA/2.0)*(0.2-0.167)
GO TO 5
4 CONTINUE
   WICT = (DIA/2.0)*(0.2-0.18)
5 CONTINUE
   VOL2 = (AREA(1)+AREA(2))/2.0)*WIDTH
CALCULATE PROPELLER BLADE VOLUME
   VOLBLO=VCL1*VOL2
RETURN
END
SUBROUTINE ELPCW1K7, SCWBAI

INPUT: BLPCW1

OUTPUT: DATE OF LAST REVISION: FEB 83

DEFINITION: HULL EFFECTIVE HURSEPOWER (HP)

THRUST COEFFICIENT

PRPELLER DIAMETER (FT)

PRPELLER REVOLUTION RATE (RPM)

WATER LENGTH (LB-F-SEC/FT)

SHIP SPEED (FT/SEC)

WAKE FRACTION

THRUST DEDUCTION

RELATIVE ROTATIVE EFFICIENCY

CONSTRAINT VARIABLE FOR PRO-

PEELLER-DEVELOPED EFFECTIVE

HURSEPOWER CONSTRAINT

(SCWBAI<1)

REAL*4 ETAO, WEIGHT, AEVAO, DIA, N, PE, PUVC, QS, TC75R, V,

RJCNL, RJSCL, R75RCU, AEAVCL, AEACU, TC75CL, TC75CU,

FGMBL, DIACU, AEAVCL, TCSTKS, RJ;

VT, TCCL, WC, WATNR, WATNL, TEMP, NCSCRW, HCL, PATM;

PMATLA, PMVLA, DIALIM, ETARR, AEADMN, TC75MN, SC;

K1, PDEV, THRT, PT, SCWBAI;

COMMON /GLODEM/ ETAO, WEIGHT, AEVAO, N, PE, PUVC, QS, TC75R, V, RJCNL,

1RJCNL, RJSCL, R75RCU, AEAVCL, AEACU, TC75CL, TC75CU, PDEB, DIALAI;

COMMON /PAR2M/VK, TC, WT, Z, WATNR, WATNL, TEMP, NCSCRW, HCL, PATM, PMATLA;

1PROMAT, DIAM, ETARR, AEADMN, TC75MN, SC;

CALCULATE THRUST DEVELOPED BY EACH PROPELLER

THRT=(K1*W*TRG*(DIAM*4)*(N/60.0)**2)

DETERMINE HULL EFFECTIVE POWER DEVELOPED BY PROPELLER(S)

PT=THRT*(1.0*WT)*V1/550.0

PEDEV=(((((1.0-TC)/(1.0-WT))**ETARR*PT)**NCSCRW)

CALCULATE CONSTRAINT VARIABLE

SCWBAI=1.0-(PEDEV/PE)

RETURN

END
SUBROUTINE LP0K2(KG, SWBAL)
SUBROUTINE: BLPCW2

INPUT

OUTPUT

DATE OF LAST REVISION: FEB 83

DELIVERED TORQUE (FT-LbF) (APP11200)
TORQUE COEFFICIENT (APP11220)
PROPPELLER DIAMETER (FT) (APP11240)
PROPPELLER REVOLUTION RATE (KPM) (APP11250)
WATER CENSITY (LBF-SEC2/FT4) (APP11260)
C CONSTRAINT VARIABLE FOR PROP- (APP11270)
PELLER REQUIRED TORQUE (SWBAL0) (APP11280)

REAL*4 ETAO, HEIGHT, AEDVAD, DIA, N, PE, POLW, QS, TC75R, V,
1 RJCNL, RJCNW, R75FCL, R75RCU, AEADCL, AEACC, TC75CL, TC75CU,
2 FCWAL, DIA2NU, AEADA, TCSTAS,
3 VU, IL, WTZ, VATR, WATNU, TEMP, NCSBN, HCL, PATM,
4 FATVA, PROCMAT, DIALIM, ETARK,
5 KG, QASCD, SWBAL

COMMON /GLOBCH/ ETAO, HEIGHT, AEDVAD, DIA, N, PE, PDIVD, QS, TC75R, V, RJCNL, APP11270
1 RJCNW, R75FCL, R75RCU, AEADCL, AEACC, TC75CL, TC75CU, PONWAL, DIA2NU,
2 AEADA, TCSTAS, RJ

COMMON /PARIM/ VU, IL, WTZ, VATR, WATNU, TEMP, NCSBN, HCL, PATM, PWATVA,
1 PROCMAT, DIALIM, ETARK, AEADNM, TC75NN, SC

CALCULATE THE TORQUE ABSORBED BY PROPPELLER

QSAED=(KG*WTR0*1(DIA**5)(L(N/0.01)**2)) (APP11450)

CALCULATE CONSTRAINT VARIABLE

SWBAL=1.0-(QSAED/CS)

END

END
SUBROUTINE ELPCW3(KT,KC,SOMBLP,SOMBLU)

INPLT               OUTPUT

KT                  THRUST COEFFICIENT
KQ                  THRUST COEFFICIENT
PE                  HULL EFFECTIVE HURSEPOWER
NQ                  HULL EFFECTIVE HORSEPOWER(HP)
QS                  PRECEPER REVOLUTION RATE
NOSCRW              NUMBER OF PROPELLERS
ETARR               RELATIVE ROTATIONAL EFFICIENCY
SOMBLP              DELIVERED POWER
SOMBLU              CONSTRAINT (SOMBLQ0)

REAL*4 ETAO,WEIGHT,AEQVAO,DIA,N,PE,PDIV,E,TS,T75R,T75C,R75RCL,R75RL,AEAGCL,AEAGCU,T75CL,T75CU,
1
2
3
4
5
COMMON /GLOECN/ETAG,WEIGHT,AEQVAO,DIA,N,PE,PDIV,E,TS,T75R,T75C,R75RCL,R75RL,AEAGCL,AEAGCU,T75CL,T75CU,

P11=3.14159265

CALCULATE THRUST DEVELOPED BY EACH PROPELLER

THRT=(KAT+MATR)*(DIA**4)*(N/60.0)**2

DETERMINE EFFECTIVE POWER DEVELOPED BY PROPELLER(S)

PI=(THRT/10.0-0.5)**3/550.0

PEDEV=(((1.0-0.5=1.0)**ETARR*PI)*NOSCWR

CALCULATE THE TQUE ABSORBED BY PROPELLER

CPABD=(KT*KAT+MATR)*(DIA**5)*(N/60.0)**2

DATE OF LAST REVISION: FEB 83

APP11560

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APP11560
CALCULATE THE POWER ABSORBED BY THE PROPELLER

PDAED = 12.0 * FII * CPABD * N1 / 33000.0

CALCULATE THE POWER DELIVERED TO THE PROPELLER

PD = 12.0 * FII * QS * N1 / 33000.0

DETERMINE CONSTRAINT VARIABLES

SWELP = 1.0 - (PEOEY/FE)

SWEPLC = (PDAED/PC) - 1.0

RETURN

END
SUBROUTINE CALCQ(J,PDIVD,AEDVAC,Z,REYAC,KQ)

INPT            OUTPUT
AEDVAC          EXPANDED AREA RATIO
PDIVD           PITCH-LIMITER RATIO
Z               NO. OF BLADES
J               ADVANCE RATIO
REYNO           REVOLNS NO. 3/4 RADIUS
KQ              CORRECTED FOR T/C 3/4 RADIUS

REAL*4 J,PDIVD,AEDVAC,Z,REYNO,K,KG1,KG2,KU1,KG4,KQ5,KQ6,KQ7,KQ8,
1
KQ9,KQ10,DELK1,DELK2,DELK3,REYAC

1
FIRST, CALCULATING "KQ1" THRU "KQ10".....

KQ1=(0.037929681*J**2)+(0.008665231*J*PDIVD)+
1
KQ2=(0.1084091*J*PDIVD*AEDVAC)+(0.0889581*J**2*PDIVD*AEDVAC)+
1/2
(KQ1=0.168511*PDIVD*AEDVAC)+(0.03150711*J**2)+
1/2
KQ3=(0.2394491*PDIVD*Z)+(0.0474319*J**2*PDIVD*Z)+
1/2
(KQ2=0.2685031*PDIVD**2+AEDVAC*Z)+(0.0438288)*PDIVD*AEDVAC*Z)+
1/2
KQ4=(0.5586821*J**3*AEDVAC)+(0.0161866*PDIVD**3*AEDVAC)+
1/2
(KQ3=0.5160861*J**3*AEDVAC)+(0.0159661*AEDVAC**2)+
1/2
KQ5=(0.1962831*J**3+(AEDVAC**2)+(0.0502782*PDIVD)+
1
(AEDVAC**2)+(0.030551)*J**3)*PDIVD*(AEDVAC**2)+
1/3
((0.0373221*J**2*PDIVD**2)+(AEDVAC**2)+
1/3
(KQ6=(0.030024)*PDIVD**2)+(AEDVAC**2)+(0.0106854)*J**3)*Z)+
1/2
((0.011903)*J**3)+(AEDVAC**3)+Z)+(0.0031912)*PDIVD**6)+
1/2
KQ7=(0.0112121*PDIVD**6)+(AEDVAC**2)+(0.00383637)*J**3)+
1/2
(AEDVAC**2)+Z)+(0.0126803)*PDIVD**2)+(AEDVAC**2)+Z)+
1/2
((0.0334268)*PDIVD**6)+(AEDVAC**2)+Z)+
1/2
KQ8=(0.0013591)*PDIVD**2)+(Z**2)+(0.0001251)*J**3)+(PDIVD**2)+
1/2
(Z**2)+((0.00027228)*J**3)+(PDIVD**2)+(Z**2)+
1/2
((0.0259551)*J**3)+(AEDVAC**2)+(Z**2)+((0.0083265)*J**3)*AEDVAC*+
1/2
(KQ9=(0.0153344)*PDIVD**2)+(AEDVAC**2)+(Z**2)+(0.00302603)*
1/2
(PDIVD**2)+(AEDVAC**2)+(Z**2)+(0.001643)*AEDVAC**2)+(Z**2)+
1/2
((0.0042539)*PDIVD**2)+(AEDVAC**2)+(Z**2)+((0.00145)*AEDVAC**2)+
1/2

APP 12190
APP 12200
APP 12220
APP 12230
APP 12240
APP 12250
APP 12260
APP 12270
APP 12280
APP 12290
APP 12300
APP 12310
APP 12320
APP 12330
APP 12340
APP 12350
APP 12360
APP 12370
APP 12380
APP 12390
APP 12400
APP 12410
APP 12420
APP 12430
APP 12440
APP 12450
APP 12460
APP 12470
APP 12480
APP 12490
APP 12500
APP 12510
APP 12520
APP 12530
APP 12540
APP 12550
APP 12560
APP 12570
APP 12580
APP 12590
APP 12600
APP 12610
APP 12620
APP 12630
APP 12640
APP 12650
APP 12660
3 \((\langle C00 \cdot 69243 \rangle * (J \star 3) * (PDIVD \star 3) * (AEDVAC \star 2) * (L \star 2))\)

\(KW10 = ((-0.01666654) \star (PDIVD \star 6)) + ((0.0160818) \star (AEVAD \star 2))\)

\(DELKQ1 = (-0.0591412) + ((0.0000056) \star (PDIVD \star 1))\)

\(DELKQ2 = ((-0.0000056) \star (PDIVD \star 6)) + ((0.0000056) \star (PDIVD \star 2))\)

\(DELKQ3 = ((-0.0000056) \star (PDIVD \star 1)) + ((-0.0000056) \star (PDIVD \star 2))\)

\(DELKQ = DELKQ1 + DELKQ2 + DELKQ3\)

\(KN = (KQ1 + KQ2 + KQ3 + KQ4 + KQ5 + KQ6 + KQ7 + KQ8 + KQ9 + KW10) \star DELKQ\)

RETURN ENC

NEXT, CALCULATE LOGARITHMIC REYNOLDS NUMBER FACTOR "KEYFAC"

WRITE (6, *RENG, REYAO, REYNG KEYFAC = ALG210 (RENG) 1.0, 0.301

THEN, CALCULATE "DELKQ = DELKQ1 + DELKQ2 + DELKQ3"........

FINALLY, CALCULATE TRUST COEFFICIENT "KC" WHERE

\(KQ = KQ1 + KQ2 + KQ3 + KQ4 + KQ5 + KQ6 + KQ7 + KQ8 + KQ9 + KW10 + DELKQ\)
SUBROUTINE CALK(J,PDIV,AEVACL,Z,REYNC,KT)

SUBROUTINE: CALK

DATE OF LAST REVISION: FEB 83

INPUT OUTPUT
AECVAG EXPANDED AREA RATIO
PDIV PITCH-CIETER RATIO
Z NEC OF BLADES
REYNO ADVANCE RATIO
KT KEYNLE'S NO. 3/4 RADIUS

REAL*4 J,PDIV,AEVACL,Z,REYNC,KT,KT1,KT2,KT3,KT4,KT5,KT6,KT7,KT8,

CELK,DELT1,DELT2,DELT3,REYFAC

1 FIRST, CALCLATING "KT1" THRU "KT8"........

KT1=CGE0456+(1.206541*J)+(1.366231*PDIV)+

1 (*1.58114*PDIV*2)+(*1.435811*J*2)+(*1.623841*AEVACL)+

APP1360

KT2=(1.401457*J)+(*1.206541*PDIV)+(*1.435811*AEVACL)+

1 (*1.58114*PDIV*2)+(*1.623841*AEVACL)+

APP1380

KT3=(1.595433*J)+(1.206541*PDIV)+(*1.0535051*J*2)+(1.0143481*PDIV*2)+

APP1400

KT4=(1.106626*J)+(*1.206541*PDIV)+(*1.0132941*AEVACL)+

1 (*1.353981*PDIV*2)+(*1.060384071*PDIV*2)+

APP1420

KT5=(1.04351*J)+(*1.206541*PDIV)+(*1.0544751*J*2)+(*1.206541*AEVACL)+

1 (*1.0132941*PDIV*2)+(*1.353981*PDIV*2)+

APP1440

KT6=(1.031791*J)+(*1.206541*PDIV)+(*1.0143481*J*2)+(*1.0535051*J*2)+

1 (*1.0544751*J*2)+(*1.206541*AEVACL)+

APP1460

KT7=(1.031791*J)+(*1.206541*PDIV)+(*1.0132941*AEVACL)+

1 (*1.0544751*J)+(*1.206541*AEVACL)+

APP1480

KT8=(1.031791*J)+(*1.206541*PDIV)+(*1.0132941*AEVACL)+

1 (*1.0544751*J)+(*1.206541*AEVACL)+

APP1500

NEXT, CALCULATE LOGARITHMIC REYNOLDS NUMBER FACTOR "REYFAC"

WRITE(*,REYNC,RENC)

REYFAC=ALOG10(REYNC)G.301

THEN, CALCULATE "DELT=DELT1+DELT2+DELT3"......

APP1520
DELT1 = (-0.003333756) * AEDVAC * (J**2) +
DELT2 = (-0.00757792) * (REYFAC**2) * AEDVAC * (J**2) +
DELT3 = (-0.000276305) * (REYFAC**2) * (PDIVD**2) * (J**2) +

FINALY, CALCULATE THRUST COEFFICIENT "KT" WHERE
KT = KT1 + KT2 + KT3 + KT4 + KT5 + KT6 + KT7 + KT8 + DELKT
RETURN
END

APP13450
APP13460
APP13470
APP13480
APP13490
APP13500
APP13510
APP13520
APP13530
APP13540
APP13550
APP13560
APP13570
APP13580
APP13590
APP13600
APP13610
SUBROUTINE CALCQS(KG, SCS)

INPUT

KQ, DIA, N, WATRO

OUTPUT

TQ, DIA, N, WATER DENSITY (LBF-SEC2/FT4)

DATE OF LAST REVISION: FEB 83

DELIVERED TORQUE (FT-LBF)

REAL*4 ETA0, WEIGHT, AEVDAD, DIA, N, PE, PD1VC, QS, TC75R, V,

RJCNL, RJCNU, R75RCL, R75RCL, AEACL, AEACC, TC75CL, TC75CU,

VK, TL, W1, 2, WATRw, WATNw, TEMP, NCSCRW, HCL, PATM,

F, AIA, PROMAT, CIAIM, ETARR, AEADMA, TC75MN, SC,

COMMON /GLOCE/N, ETA0, WEIGHT, AEVDAD, DIA, N, PE, PD1VC, QS, TL, 75R, V, RJCNL,

R75RCL, R75RCL, AEACL, AEACC, TC75CL, TC75CU, POMBAL, CIAA,

CIAA, ICSTFS, W1, 2, WATRO, WATNw, TEMP, NCSCRW, HCL, PATM, PWATVA,

COMMON /PAR2N/K, TL, W, 2, WATRO, WATNw, TEMP, NCSCRW, HCL, PATM, PWATVA,

1PRMAT, CIAIM, ETARR, AEADMA, TC75MN, SC

CALCULATE DELIVERED TORQUE REQUIRED BY PROPULSER

SOS = KG * WATF0 * (CIAA**5) * (N/60)**2

RETURN

END
SUBROUTINE CALCPE(KT,SPE)

INPUT     OUTPUT

KT         THRUST COEFFICIENT
DIA        PROPELLER DIAMETER (FT)
N          PROPELLER REVOLUTION RATE (RPM)
WATRO      WATER DENSITY (LBF-SEC2/FT4)
TD         THRUST DELECTIOIN
HT         TAYLOR MAKE FRACTION
V           VELOCITY (FT/SEC)
SPE        EFFECTIVE POWER (HP)

REAL*4 ETAO,WEIGHT,AEDVAO,DIA,N,PE,POIVC,US,TC75K,V,
RJCNL,RJCNU,R75KCL,R75KCU,AEACL,AEACC,TC75CL,TC75CU,
FGWBL,Diacnu,Aeadcv,TCSTK,RS,
WK,IT,MT,2,WATRC,WTNU,TEMPO,NSCRM,HCL,PATH,
PRATIA,PROMAT,DIALM,ETARK,EAADMN,TC75MN,SC;

COMMON /GLOLCH/ETAO,WEIGHT,AEDVAO,DIA,N,PE,POIVC,US,TC75K,V,RJCNL,
RJCNU,R75KCL,R75KCU,AEACL,AEACC,TC75CL,TC75CU,POMBL,Diacnu,
Aeadcv,TCSTK,RS,
COMMON /PARAM/VR,TC,MT,2,WATRO,WTNU,TEMPO,NSCRM,HCL,PATH,PRATIA,
PRMAT,DIALM,ETARK,EAADMN,TC75MN,SC;

CALCULATE THRUST DEVELOPED BY PROPELLER

T=(KT*WATRO*(DIA**4)*((IN/60.0)**2))

CALCULATE EFFECTIVE HORSEPOWER DEVELOPED BY PROPELLER

SPE=(((1.0-TC)/(1.0-HT))*((T*(1.0-HT)*V)/550.0)
RETURN
END
SUBROUTINE CAVCN(ITA,SEAOCV)

SUBROUTINE CAVCN

INPUT OUTPUT

PATM ATMOSPHERIC PRESSURE (PSIA)

WATRO WATER DENSITY (LBF-SEC2/FT4)

PWATVA VAPORIZATION PRESSURE FOR WATER (PSIA)

HCL DEPTH OF PROPELLER SHAFT (FT)

CENCLINE CENTERLINE (FT)

THRLST THRUST EFFICIENT

DIA PROPELLER DIAMETER (FT)

N PROPELLER REVOLUTION RATE (RPM)

Z NO. OF BLADES

NOSCRW NO. OF PROPELLERS

AEVDAO PROPELLER EXPANDED AREA RATIO

SEAOCV CONSTRAINT VARIABLE FOR PRO-

PELLER EXPANDED AREA RATIO

CONSTRAINT (SEAOCV<0)

REAL*4 ETAO, WEIGHT, AEVDAO, DIA, N, PE, FDIV, GS, TC75R, V,

1 RJCNU, RJCNU, TC75CL, TC75CU, AEAGL, AEACLU, TC75LCl, TC75CU,

2 FCWAL, DIAJCU, AEACLV, TCSTKS, RJ

3 VK, IL, WT, WATRO, WATU, TEMP, NOSCRW, HCL, PATM,

4 FLATVA, PROMAT, DIAIM, ETARR, AEADMA, TC75MN, SC,

5 KI, PNMNP, THRSI, SEACMN, SEAOCV

COMMON /GLOECN/ ETAO, WEIGHT, AEVDAO, DIA, N, PE, FDIV, GS, TC75R, V, RJCNU

1 RJCNU, RJCNU, TC75CL, TC75CU, AEAGL, AEACLU, TC75LCL, TC75CU, FCWAL, DIAJCU,

2 AEACLV, TCSTKS, RJ

COMMON /PROMAT/VK, IL, WT, WATRO, WATU, TEMP, NOSCRW, HCL, PATM, PWATVA,

1 PROMAT, DIAIM, ETARR, AEADMA, TC75MN, SC

CALCULATE DIFFERENCE BETWEEN STATIC PRESSURE AT SHAFT CENTERLINE

& WATER VAPORIZATION PRESSURE

FPVAPV=(FATP*144.0)*(WATRO*32.174*HCL)-(PWATVA*144.0)

DETERMINE MINIMUM REQUIRED EXPANDED AREA RATIO FOR PROPELLER(S)

USING "KELLER" CRITERIA FROM RELATION (13), REF 2

THRS=(K1*WATRO*(DIA**4)/(N/60.0)**21)

SEACMN=((1.3*(0.3*Z**2)1*THRS)**((DIA**2)*FPMNP))

CORRECT ACCORDING TO NUMBER OF PROPELLERS

IF(1 .NE. NOSCRW .EQ. 1.0) GO TO 1
SEACHN = SEACHN + 0.2
GO TO 3
1 CONTINUE
IF (NOT (NSCRW EQ 2.0)) GO TO 2
SEACHN = SEACHN + 0.1
GO TO 3
2 CONTINUE
SEACHN = SEACHN + 0.0
3 CONTINUE
AEACHN = SEACHN

DETERMINE CONSTRAINT VARIABLE
SEADCY = (SEACHN/AEDVAD) - 1.0
RETURN
END
## SUBROUTINE CH75RA(C75R)

### DATE OF LAST REVISION: Feb 83

<table>
<thead>
<tr>
<th>INPUT</th>
<th>OUTPUT</th>
</tr>
</thead>
<tbody>
<tr>
<td>AECDVAO</td>
<td>EXPANDED AREA RATIO</td>
</tr>
<tr>
<td>DIA</td>
<td>PROPELLER DIAMETER (FEET)</td>
</tr>
<tr>
<td>Z</td>
<td>NO. OF ELADES</td>
</tr>
<tr>
<td>C75R</td>
<td>CHORD LENGTH AT 3/4 RADIUS (FEET)</td>
</tr>
</tbody>
</table>

**REAL**:
- ETAO, WEIGHT, AECDVAO, DIA, N, PE, FDIVD, QS, TC75R, V
- FJCNL, RJCNL, R75RCL, R75RCU, AEACL, AEACC, T75CL, T75CU
- FGCRD, DIACNU, AEACVC, TCSKRS
- RJ
- VK, TL, MT, Z, WATRO, WATNU, TEMP, NCSCKW, HCL, PATM
- PMATL, PRMAYT, DIAL1K, E1ARR, AEADMN, TL75MN, SC

**COMMON**:
- ELDECM, ETAO, WEIGHT, AECDVAO, DIA, N, PE, FDIVD, QS, TC75R, V, RJCNL
- R75RCL, R75RCU, AEACVC, AEACL, T75CL, T75CU, POWBAL, DIACNU
- AEACC, TCSKRS
- RJ
- PARAM, VK, TL, Z, WATRO, WATNU, TEMP, NCSCKW, HCL, PATM, PWATVA
- 1PRMAT, CIA1K, E1ARR, AEADMN, TL75MN, SC

**CALCULATE CHORD LENGTH AT 3/4 RADIUS USING RELATION (117), REF 2**

- C75R = 12.073 * AECDVAO * DIA/2

**RETURN**

**END**
### SUBROUTINE CNFGLD

**DATE OF LAST REVISION:** APR 83

**DEFINITION**

**INPUT**

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
<th>APP</th>
</tr>
</thead>
<tbody>
<tr>
<td>DIA</td>
<td>PROPELLER DIAMETER (FT)</td>
<td>15300</td>
</tr>
<tr>
<td>N</td>
<td>PROPELLER REVOLUTION RATE (RPM)</td>
<td>15360</td>
</tr>
<tr>
<td>PDIVD</td>
<td>PITCH-DIAMETER RATIO</td>
<td>15300</td>
</tr>
<tr>
<td>Z</td>
<td>AC, CF PROPELLER BLADES</td>
<td>15390</td>
</tr>
<tr>
<td>PRGMAT</td>
<td>PROPELLER MATERIAL IDENTIFIER</td>
<td>15400</td>
</tr>
<tr>
<td></td>
<td>1: CAST IRON</td>
<td>15420</td>
</tr>
<tr>
<td></td>
<td>2: CAST STEEL</td>
<td>15460</td>
</tr>
<tr>
<td></td>
<td>3: TYPE 2 BRONZE</td>
<td>15430</td>
</tr>
<tr>
<td></td>
<td>4: TYPE 4 NI-AL BRONZE</td>
<td>15440</td>
</tr>
<tr>
<td></td>
<td>5: STAINLESS STEEL</td>
<td>15450</td>
</tr>
</tbody>
</table>

**COMMON /AREELD/**

LOCATION OF BLADE CROSS-SECTIONAL AREA CENTROID WITH RESPECT TO GENERATOR LINE (FEET)

**COMMON /CGX/**

LOCATION OF BLADE CROSS-SECTIONAL AREA CENTROID WITH RESPECT TO PITCH-REFERENCE LINE (FEET)

**COMMON /CFGFD/**

CENTRIFUGAL FORCE COMPONENTS, ALONG THE PROPELLER RADIUS, PARALLEL TO GENERATOR LINE, WHICH ACT ON A BLADE SECTION AT ITS NEUTRAL AXES ORIGIN (LBF)

**COMMON /CMCNB/**

CENTRIFUGAL BENDING MOMENT COMPONENTS, ALONG THE PROPELLER RADIUS, NORMAL TO THE PITCH REFERENCE (CHORD) LINE, WHICH ACT ON A BLADE SECTION AT ITS NEUTRAL AXES ORIGIN (FT-LBF)

**COMMON /CMCL/**

CENTRIFUGAL BENDING MOMENT COMPONENTS, ALONG THE PROPELLER RADIAL, NORMAL TO THE PITCH REFERENCE (CHORD) LINE, WHICH ACT ON A BLADE SECTION AT ITS NEUTRAL AXES ORIGIN (FT-LBF)

**REAL*4**

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
<th>APP</th>
</tr>
</thead>
<tbody>
<tr>
<td>ETA, WEI</td>
<td>WEIGHT, AEOVAD, DIA, N, PE, PDIVD, QS, TC75R, V,</td>
<td>15740</td>
</tr>
<tr>
<td></td>
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<tr>
<td>RJCL, RJCN, R75RCL, R75RCU, ACOCL, AEALCU, TC75CL, TC75CU,</td>
<td>15790</td>
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<tr>
<td>FCWAD, DIAC, AEALCU, TCSTAS,</td>
<td>15700</td>
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<tr>
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<tr>
<td>VK, WC, WT, Z, WATC, WATNU, TEMP, NGSCW, HCL, PATM,</td>
<td>15770</td>
<td></td>
</tr>
</tbody>
</table>
4  FLAT1A, PRCMAT, EIALIN, ETARR,
5  FLAT5R, FLAT5R, RT5R, KT, KG
REAL*4 RFALA(10), RFALR(10), ICXNXA(10), RIVYNA(10)
REAL*4 LMSL, SUMSV, SUMSVT, SUMSVS
REAL*4 SMALL(10), SMALL(10), SMALL(10), SMAIMA(10),
1.5
2  SINBET(10), CBEBET(10),
3  SUN1(10), SUMR(10), SUMT(10), SUMA(10),
REAL*4 CMGBR(10), CMGBR(10), CMGBR(10), CMGBR(10), CMGBR(10), CMGBR(10)
INTEGER*4 IP, IRP, KCOUNT,
COMMON /GLOED/ ETAO, WEIGHT, AEFDVNC, DIAG, NPE, PD, PVMUS, TG75R, VRJCN,
1RJCN3, RT5C51, RT5CL, AEMCXL, AEMCXL, IC75CN, PGMAL, CIACNU,
2AECCV, TCSIFS, RU
COMMON /PARZV, WTR, WATR, WATNU, TEMP, NECDR, HCL, PATM, PWATVA,
1PRMAT, EIALIN, ETARR, AEADMN, IC75MN, SC
COMMON /AREELD, AREA
COMMON /CGX, YCG
COMMON /CGY, VCG
COMMON /CMXH, RIVYNA
COMMON /CMXH, RIXXAA
COMMON /CMEMX, CMCGN
COMMON /CMENM, CMCBL
COMMON /CMFDM, CMCGN
PI=3.141592654
CALCULATE RAKE ANGLE IN RADIANS
ETA=15.0*(PI/180.0)
SPECIFY WEIGHT DENSITY OF MATERIAL SELECTED WHERE...
PRCMAT   MATERIAL   WEIGHT DENSITY (lbf/in**3)
1   CAST IRON   .260
2   CAST STEEL   .284
3.5   TYPE 3 BRONZE   .305
4   TYPE 4 NI AL BRONZE   .278
5   STAINLESS STEEL   .283
IF (PRCMAT.EQ.1.CMWD.EQ.260
IF (PRCMAT.EQ.2.CMWD.EQ.284
IF (PRCMAT.EQ.3.CMWD.EQ.305
IF (PRCMAT.EQ.4.CMWD.EQ.278
IF (PRCMAT.EQ.5.CMWD.EQ.283
DETERMINE VALUES FOR...
SMALL(1R) DISTANCE TO THE PITCH REFERENCE LINE, ALONG THE
PROPELLER RADIUS, WITH RESPECT TO A LINE NORMAL
IC THE PROPELLER SHAFT AXIS AND PASSING THROUGH
THE INTERSECTION OF THE GENERATOR LINE AND THE
PROPELLER SHAFT AXIS (FEET)

SMALLA(IR)
DISTANCE, PARALLEL TO THE PROPELLER SHAFT AXIS,
OF EACH BLADE SECTION NEUTRAL AXES ORIGIN, GIVEN
TO THE INTERSECTION OF THE PITCH REFERENCE LINE
AND THE GENERATOR LINE (FEET)

SMALLT(IR)
DISTANCE, NORMAL TO THE PROPELLER SHAFT AXIS,
OF EACH BLADE SECTION NEUTRAL AXES ORIGIN, GIVEN
BY COORDINATES (XCG(IR), YCG(IR)), WITH RESPECT
TO THE INTERSECTION OF THE PITCH REFERENCE LINE
AND THE GENERATOR LINE (FEET)

*** FOR EACH BLADE SECTION ALONG THE PROPELLER RADIUS

DO 9 IR=1,16
   IF(NCT(IR, EQ.0) .AND. NCT(IR, EQ.2)) GO TO 7
   IF(NCT(IR, EQ.3)) GO TO 2
   RC=0.822
   GC TO 6
   CONTINUE
   IF(NCT(IR, EQ.4)) GO TO 3
   RC=0.887
   GC TO 6
   CONTINUE
   IF(NCT(IR, EQ.5)) GO TO 4
   RC=0.952
   GC TO 6
   CONTINUE
   RF=1.00
   CONTINUE
   DENOM=SORT1((RF/PI*DVC)**2)+(PI**2)
   SIBET(I,N)=RF/PI*DVC/DENOM
   CSBET(I,N)=(PI/N)**2/DENOM
   GC TO 6
   CONTINUE
   DENOM=SORT1((PI*DVC)**2)+(PI**2)
   SIBET(I,N)=PI*DVC/DENOM
   CSBET(I,N)=(PI**2)/DENOM
   GC TO 6
   CONTINUE
   SMALLA(IR)=(DIA/2.0)*(FLOAT(IR)/.001)*TAN(ETA)
   SMALLT(IR)=(XCG(IR)*SINBET(I,N)+YCG(IR)*COSBET(I,N))
   SMALLT(IR)=(XCG(IR)*COSBET(I,N)+YCG(IR)*SINBET(I,N))

END
SMAL\{IR\} = SMALL\{IR\} - SMALL\{IR\}

CONTINUE

CALCULATE TABULAR SUMMATIONS FOR INTEGRATION ALONG THE PROPELLER RADIUS

DO 10 IR = 2, 5
   IRF = IR + 1
   SLH = IRF * AREA\{IR\} * AREA\{IR\} + (FLAT\{IR\} * AREA\{IR\})
   SLW = IRF * SMALL\{IR\} * AREA\{IR\} + (SMALL\{IR\} * AREA\{IR\})
   SUMA = SMAL\{IR\} * AREA\{IR\} + (SMAL\{IR\} * AREA\{IR\})

CONTINUE

INTEGRATE ALONG THE PROPELLER RADIUS TO DETERMINE THE FORCE AND BENDING MOMENT COMPONENTS ACTING ON A BLADE SECTION AT ITS NEUTRAL AXIS ORIGIN, WHICH ARE IMPLIED BY CENTRIFUGAL LOADING OF THE BLADE ELEMENT ABOVE THE BLADE SECTION UNDER CONSIDERATION

DO 12 IR = 2, 5
   KCLAT = IR
   SUMV = 0.0
   SLV = SUMV * 0.0
   SLV = SUMV * 0.0
   SUMVA = SUMVA * 0.0
   DC 111 = KCLAT * 5
   SLMSV = SUMV * SUMV
   SLMSV = SUMV * SUMV
   SLMSV = SUMV * SUMV
   SLMSVA = SUMVA * SUMVA

CONTINUE

DETERMINE BLADE ELEMENT VOLUME (FT**3) ABOVE THE BLADE SECTION UNDER CONSIDERATION

VCLC\{IF\} = 0.5 + (CIA / 2.0) * (SUMV)

DETERMINE RADIAL FRACTION OF THE BLADE ELEMENT VOLUME'S CG WITH RESPECT TO THE PROPELLER SHAFT AXIS

XRFGO\{IR\} = (SUMVR / SUMSV) * 10.0

DETERMINE DISTANCE (FEET) FROM THE GENERATOR LINE, NORMAL TO THE PROPELLER SHAFT AXIS, OF THE BLADE ELEMENT VOLUME'S CG WITH RESPECT TO THE PROPELLER SHAFT AXIS

BIGTO\{IR\} = (SUMSVT / SUMSV)
DETERMINE DISTANCE (FEET) FROM THE GENERATOR LINE, PARALLEL TO THE PROPELLER SHAFT AXIS, OF THE BLADE ELEMENT VOLUME'S CG WITH RESPECT TO THE PROPELLER SHAFT AXIS

BIAG01(IR)= (SUMSVA/SUMSV)

DETERMINE DISTANCE (FEET) FROM THE GENERATOR LINE, NORMAL TO THE PROPELLER SHAFT AXIS, OF THE BLADE ELEMENT VOLUME'S CG WITH RESPECT TO THE BLADE SECTION UNDER CONSIDERATION

SMG01(IR)=((FLOAT(IR)/10.0)*XBCGO(IR))*BIG01(IR)

DETERMINE DISTANCE (FEET) FROM THE GENERATOR LINE, PARALLEL TO THE PROPELLER SHAFT AXIS, OF THE BLADE ELEMENT VOLUME'S CG WITH RESPECT TO THE BLADE SECTION UNDER CONSIDERATION

SMG01(IR)=BIG01(IR)-((DIA/2.0)*FLCAT(IR)/10.01)*TAN((TA))

CALCULATE FORCE AND BENDING MOMENT COMPONENTS WHERE...

BIG01(IR) CENTRIFUGAL FORCE ACTING AT BLADE SECTION

CMCBA1(IR) BENDING MOMENT COMPONENT, IMPOSED BY CENTRI-FUGAL LOADING, PARALLEL TO PITCH REFERENCE (CHORD) LINE OF A BLADE SECTION

CMCBL1(IR) BENDING MOMENT COMPONENT, IMPOSED BY CENTRI-FUGAL LOADING, NORMAL TO PITCH REFERENCE (CHORD) LINE OF A BLADE SECTION

RADIUS=(FLCAT(IR)/10.01)*G1A/2.01

BIG01(IR)=((MC1/12.0*VML01(IR))*((DIA/2.0)*XBCGO(IR)/3*174)*

1/2

((RADIUS/SQRT((RADIUS**2)+((SMG01(IR))**2))))

CMCBA1(IR)=BIG01(IR)*((SMG01(IR)*SINBET1(IR))**2)

1

CMCBL1(IR)=BIG01(IR)*((XG1(IR))

1

CMCBL1(IR)=(SMG01(IR)*SINBET1(IR)+YGL1(IR))

1

1 CONTINUE

RET LLA

ENC
SUBROUTINE COEFSAL(SJ,R75K,KT,KQ)

SUBROUTINE: COEFSAL

INFLY OUTPUT

ABEAOD
PDIVD
Z
S
R75R

KT
KQ

DATE OF LAST REVISION: FEB 83

EXPANDED AREA RATIO
PITCH-DIAMETER RATIO
NC OF BLADES
ADVANCE COEFFICIENT
REYNOLDS NO. 3/4 RADIUS
CORRECTED FOR T/C 3/4 RADIUS
THRUST COEFFICIENT
TORSION COEFFICIENT

REAL*4 ETAO,WEIGHT,AEUVAO,DIA,N,PE,PDIVD,QS,TC75R,VT
1 RJCNL,RJCNU,R75C,R75BU,AEADCL,AEACCU,TC75CL,TC75CU,
2 FOWH,DIACAU,AEACU,TCSTUS,RJ,
3 W4,TC,W4,2,WATRO,WATNU,TEMP,NCSRM,HCL,PATM;
4 PRATVA,PRMAT,DIALIM,ETAKR,EAOMN,TC75NN,SC;
5 R75R,KT,KQ,SJ

COMMON /GLOCM/ETAO,WEIGHT,AEUVAO,DIA,N,PE,PDIVD,QS,TC75R,VT,RJCNL,
1RJCNU,R75C,R75BU,AEADCL,AEACCU,TC75CL,TC75CU,PWBAU,DIACNU,
2AEACU,TCSTUS,RJ

COMMON /PARAM/VK,LD,W4,2,WATRO,WATNU,TEMP,NCSRM,HCL,PATM,PWATVA,
1PRMAT,DIALIM,ETAKR,EAOMN,TC75NN,SC

CALCULATE THRUST & TORQUE COEFFICIENTS USING THE WAGENINGEN SERIES

POLYNOMIALS GIVEN IN TABLES (5) AND (6), REF 2

CALL CALKT(SJ,PDIVD,AEUV,2,R75K,KT)
CALL CALKQ(SJ,PDIVD,AEUV,2,R75K,KQ)
RETURN
END
SUBROUTINE CICNUA(SIACNU)

DATE OF LAST REVISION: FEB 83

INPUT

OUTPUT

DEFINITION

DIA

DIALIM

SIACNU

DESCRIPTION

SIACNU

REAL*4 ETA0, WEIGHT, AEVDAU, DIA, A, PE, PD1DL, GS, TC75R, V

1 RJCNL, JCNU, R75CCL, R75CRC, AEACL, AEACC, TC75CL, TC75CU,

2 FGBC3, DIAC, AEACL, AEACC, TCSTRS, RJ

3 VK, TC, WTZ, WATRC, WATNU, TEM, NOSCRW, HCL, PATM

4 FLATVA, PROMAT, DIALIM, ETARR, AEADMN, TC73MN, SC

5 SIACAU

COMMON /GLOECM/ ETA0, WEIGHT, AEVDAU, DIA, A, PE, PD1DL, GS, TC75R, V, RJCNL, 

1. R75CCL, R75CRC, AEACL, AEACC, TC75CL, TC75CU, POBNAL, DIAC, 

2. AEACL, AEACC, TCSTRS, RJ

COMMON /PARIM/VK, TC, WTZ, WATRC, WATNU, TEM, NOSCRW, HCL, PATM, PWATVA, 

1. PRGMAT, DIALIM, ETARR, AEADMN, TC73MN, SC

DETERMINE CONSTRAINT VARIABLE OF PROPELLER DIAMETER'S UPPER BOUND

CONTRAINT

SIACNU = (DIA/DIALIM) - 1.0

RETURN

END
SUBROUTINE EXTCN (I,AECVAQ,TC75K,AEACL,AEACCU,TC75CL,TC75CU)

REAL*4 2,AECVAQ,TC75K,AEACL,AEACCU,TC75CL,TC75CU,

SET LIMITS ON EXPANDED AREA RATIO BASED ON NUMBER OF BLADES

1

GO TO 6
1 CONTINUE

IF (.NOT. (Z .LE. 1.0)) GC TO 3

IF (.NOT. (Z .LE. 3.0)) GC TO 1

GO TO 6

2 CONTINUE

IF (.NOT. (Z .LE. 5.0)) GC TO 3

GO TO 6

3 CONTINUE

IF (.NOT. (Z .LE. 6.0)) GC TO 4

GO TO 6

4 CONTINUE

IF (.NOT. (Z .LE. 7.0)) GC TO 5

GO TO 6

IF (.NOT. (Z .LE. 3.0)) GC TO 1

IF (.NOT. (Z .LE. 5.0)) GC TO 3

IF (.NOT. (Z .LE. 6.0)) GC TO 4

IF (.NOT. (Z .LE. 7.0)) GC TO 5

GO TO 6

IF (.NOT. (Z .LE. 1.0)) GC TO 2

IF (.NOT. (Z .LE. 3.0)) GC TO 1

GO TO 6

IF (.NOT. (Z .LE. 5.0)) GC TO 3

GO TO 6

IF (.NOT. (Z .LE. 6.0)) GC TO 4

GO TO 6

IF (.NOT. (Z .LE. 7.0)) GC TO 5

GO TO 6

IF (.NOT. (Z .LE. 1.0)) GC TO 2

IF (.NOT. (Z .LE. 3.0)) GC TO 1

GO TO 6

IF (.NOT. (Z .LE. 5.0)) GC TO 3

GO TO 6

IF (.NOT. (Z .LE. 6.0)) GC TO 4

GO TO 6

IF (.NOT. (Z .LE. 7.0)) GC TO 5

GO TO 6

IF (.NOT. (Z .LE. 1.0)) GC TO 2

IF (.NOT. (Z .LE. 3.0)) GC TO 1

GO TO 6

IF (.NOT. (Z .LE. 5.0)) GC TO 3

GO TO 6

IF (.NOT. (Z .LE. 6.0)) GC TO 4

GO TO 6

IF (.NOT. (Z .LE. 7.0)) GC TO 5

GO TO 6
GO TO 6
5 CONTINUE
AEACLO=0.3
AEACUP=1.05
6 CONTINUE

DETERMINE CONSTRAINT VARIABLES FOR EXPANDED AREA RATIO CONSTRAINT
AEACCL=AEADIC-AEDVAC
AEACCU=AEVDO-AEADUP

DETERMINE CONSTRAINT VARIABLES FOR BLADE THICKNESS-TO-CHORD RATIO CONSTRAINT
ICTCL0=(.5)*(1.0-0.0125*Z1*Z2/(Z073*AEADUP))
ICTCL1=(Z0)*((1.0-0.0125*Z1*Z2/(Z073*AEADLO))
ICTCL=ICTCL0-ICTCL1
ICTCL=ICTCL0-ICTCL1
RETURN
END
SUBROUTINE FYDLC(KL,KT)
SUBROUTINE HYDOL

NAME OF LAST REVISION: APR 83

COMMON HYDMLN/

COMMON HYDMLN/

REAL*4 ETAQ,WEIGHT,AEDVAO,DIA,PDIVD,OS,TC75R,V;
RJCNL,RJCN,T5RCL,T50CL,AEADCL,AEADCU,TC75CU,TC75CL,

VGK,AK,THRC,MRV,VMTHM,PXM1,PTUX,PMW,SRM,PMAB,

REAL*4 MPN1(10),MPN2(10),XO,PHI1(10),PHI2(10),GAM1(10),T,W;

INTEGER*4 IF,

COMMON GLOECM/ETAG*WEIGHT*AEDVAO,DIA,N,PET,FDIVD,OS,TC75R,V,RJCNL,

1RJCN,R50CL,R50CU,AEADCL,AEADCU,TC75CU,TC75CL,TC75CU,POWMBL,DIACM,

2AEADCL,IAV,FCN,AK,THRC,MRV,VMTHM,PXM1,PTUX,PMW,SRM,PMAB,

COMMON /PARM/VK,TD,M,T2,MRV,MRV,VMTHM,PXM1,PTUX,PMW,SRM,PMAB,

1PRCLM,CI,M,ETAG,AEADCU,TC75MN,SC

COMMON /HYMLN/HML

P11=1.41592654

DETERMINE VALUES ALONG THE PROPULSERADIUS OF VARIOUS FUNCTIONS
OF XO AND XI DEFINED BY BRACKETED EXPRESSIONS IN RELATIONS (4),
(9) AND (19), REF 6

DO 1 IR=2,1

10 XO=(FLAT1(IR))/10.0

PF11(IR)=1.0+(XT-10.0)*

12

PHI12(IR)=1.2+(XT-10.0)*
1 CONTINUE

CALCULATE THRUST DEVELOPED BY PROPELLER

\[ T = \left( K + \frac{\pi}{2} \right) \times 4 \times (D)^2 \times (L)^2 \times (N) \times (0.0) \times (2) \]

CALCULATE TORQUE REQUIRED BY PROPELLER

\[ Q = \left( K + \frac{\pi}{2} \right) \times 4 \times (D)^2 \times (L)^2 \times (N) \times (0.0) \times (2) \]

CALCULATE BENDING MOMENTS DUE TO THRUST (BM1) AND TORQUE (BMQ) ALONG THE PROPELLER RADIUS USING EQUATIONS (10) AND (26) RESPECTIVELY, REF 8.

DO 2 IR = 2, 10

BM1(1R) = (T \times D)^2 / 2 \times 0.1 / (1 \times (PHI) / (IR) / PHI(12))

BMQ(1R) = Q / 2 \times 4 \times (GAR) / (1R) / PHI(12)

2 CONTINUE

RESOLVE CALCULATED BENDING MOMENTS INTO COMPONENTS NORMAL AND PARALLEL TO PITCH REFERENCE (CHORD) LINE FOR EACH BLADE SECTION ALONG THE PROPELLER RADIUS USING EQUATIONS (42) AND (43), REF 8.

REMEMBER TO ACCOUNT FOR PITCH REDUCTION OF FOUR BLADE (2=4.0) PROPELLERS.

DO 10 IR = 2, 10

\[ 1 \times (IR) \times (EQ) \times 4 \times 0.1 \times 0 \times 0 \times 2 \times G \times \text{TO} \times 3 \]

\[ R \times F \times 0.8 \times 2 \times G \times \text{TO} \times 7 \times C \times \text{T} \times 3 \times G \times \text{TO} \times 4 \times C \times \text{T} \times 4 \times G \times \text{TO} \times 5 \times G \times \text{TO} \times 7 \times C \times \text{T} \times 5 \times G \times \text{TO} \times 6 \times R \times F \times 0.9 \times 0 \times 0 \times 7 \times C \times \text{T} \times 5 \times G \times \text{TO} \times 7
MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS 1943-1
CONTINUE
RF=1.00
CONTINUE
DENOM=SQR((RF*PDIVD)**2)+(PII**2)
H+PN(IK)=BMT(IK)*(PII/DENOM)**
          (BMC(IK)*((RF*PDIVD)/DENCM))
H+PL(IK)=(BMT(IK)*((RF*PDIVD)/DENCM))-
          (BMC(IK)*PII/DENOM))
CONTINUE
DENOM=SQR((PLIVE**2)+(PII**2))
H+PN(IK)=(BMT(IK)+(PII/DENOM))-
          (BMC(IK)*(PLIVE/DENCM))
H+PL(IK)=(BMT(IK)*((PLIVE/DENCM))-
          (BMC(IK)*PII/DENOM))
CONTINUE
RETURN
END
SUBROUTINE JCNA(RJ,RJCNL,RJCNU)

INPUT OUTPUT

RJ RJCNL RJCNU

REAL*4 RJ,RJCNR,RJCNL,RJCNU

DATE OF LAST REVISION: FEB 83

DEFINITION

ADVANCE COEFFICIENT
CONSTRAINT VARIABLE FOR AD-VANCE COEFFICIENT LOWER BOUND
(RJCNL<0)

CONSTRAINT VARIABLE FOR AD-VANCE COEFFICIENT UPPER BOUND
(RJCNU)

DETERMINE CONSTRAINT VARIABLE FOR ADVANCE COEFFICIENT CONSTRAINT

RJCNL=RJ/1.0
RJCNL=RJCNR-RJCNL
RJCNU=RJCNL+1.0
RETURN
END
SUBROUTINE CPWFFE(RJ, KT, KQ, ETAO)

INPUT                OUTPUT
RJ                     ETAO
KT
KQ

REAL*4 RJ, KT, KQ, ETAO, PII
PII = 3.141592654

CALCULATE OPEN WATER EFFICIENCY

IF (KT .LE. 0.0) THEN
  ETAO = (RJ * KT) / (2.0 * PII * KQ)
ELSE
  ETAO = 0.0001
ENDIF
RETURN
END

DATE OF LAST REVISION: FEB 83

ACWANCE RATIO
THRUST COEFFICIENT
TORQUE COEFFICIENT
OPEN WATER EFFICIENCY

APP2C420
APP2C430
APP2C440
APP2C450
APP2C460
APP2C470
APP2C480
APP2C490
APP2C500
APP2C510
APP2C520
APP2C530
APP2C540
APP2C550
APP2C560
APP2C570
APP2C580
APP2C590
APP2C600
APP2C610
APP2C620
SUBROUTINE FOCAL(REIA)

SUBROUTINE RDCAL

DATE OF LAST REVISION: FEB 83

INPT

CLTPUT

VELOCITY (FT/SEC)

PRCFELLER REVOLUTION RATE (RPM)

ADVANCE RATIO

WAKE FRACTION

PRCFELLER DIAMETER (FEET)

REAL*4 ETAO,WEIGHT,AEVUAV,CIU,N,PE,PDIVC,US,TCl75R,V,
RJCL,RCJNU,RTILC,R75KC,EAACL,AEACL,TC75CL,TC75CU,
FOMFCL,DIAICNU,AEACLV,TCSTRS,RJ,
K,MT,Z,WATRC,WATNU,TEMPT,NDONR,HCL,PATM,
PENAT,PMAT,DIARIN,ETARR,AEADNU,TC75MN,SC,
REIA

COMMON /GLOECM/ETAO,WEIGHT,AEVUAV,DIU,N,PE,PDIVU,US,TCl75R,V,RJCU,
RJCNL,R75RCL,R75RC,AEACL,AEACL,TC75CL,TC75CU,POWBAL,DIAICNU,
ZAEACL,TCSTRS,RJ,
COMMON /PARRT/VN,MT,Z,WATRK,WATNU,TEP,TNDONR,HCL,PATM,PWATVA,
IPCMAT,CIUIN,ETARR,AEADNU,TC75MN,SC

CALCULATE PROPPELLER DIAMETER

RDIAM=W/41 .C-MTI/11111/N*EO,DJ*RJ)

RETURN

END
SUBROUTINE KEYCN(A(R75R, R75RCL, R75RCU)

SUBROUTINE: KEYCN

INPUT

OUTPUT

R75R

REYNOLDS NO. 3/4 RADIUS

(R75RCL = CORRECTED FOR I/C 3/4 RADIUS APP21C40)

R75RCL

C0STRAINT VARIABLE FOR KEY-

NGLDS. NL. (CORRECTED)

R75RCU

(LOWER BOUND) (R75RCL<0)

C0STRAINT VARIABLE FOR KEY-

NGLDS. NO. (CORRECTED)

(UPPER BOUND) (R75RCU<0)

REAL*4 F75R, R75RCN, R75RCL, R75RCU

DETERMINE CONSTRAINT VARIABLE FOR CORRECTED REYNOLDS NO. CONSTRAINT

R75RCN=F75R/12000.000

R75RCL=1.0-F75RCN

R75RCU=R75RCN-1.000

RETURN

END
SUBROUTINE FEY75R(C75R,R75R)

SUBROUTINE: REY75R

INPUT

OUTPUT

C75R

CHORD LENGTH AT 3/4 RADIUS

(N FEET)

N

PROPPELLER REVsOLUTIONS (RPM)

DIA

PROPPELLER DIAMETER (FEET)

2

NO. OF BLADES

TC75R

BLADE SECTION THICKNESS-TO-

CHORD RATIO AT 3/4 RADIUS

AEDVAC

EXPANDED AREA RATIO

WATNU

KINEMATIC VISCOSITY

R 75R

REYNOLDS NO. AT 3/4 RADIUS

CORRECTED FOR CORRECTED FCR

BLADE THICKNESS EFFECTS

REAL*4 ETAO,HEIGTH,AEDVAD,OIA,N,PEDIVO,QS,TC75R,V,
1
VRJCLM,RJCCU,R75FCL,R75RCU,AEACU,AEACCU,TC75CL,TC75CU,
2
VRJCLM,RJCCU,R75FCL,R75RCU,AEACU,AEACCU,TC75CL,TC75CU,
3
VRJCLM,RJCCU,R75FCL,R75RCU,AEACU,AEACCU,TC75CL,TC75CU,
4
VRJCLM,RJCCU,R75FCL,R75RCU,AEACU,AEACCU,TC75CL,TC75CU,
5
VRJCLM,RJCCU,R75FCL,R75RCU,AEACU,AEACCU,TC75CL,TC75CU,
1
VRJCLM,RJCCU,R75FCL,R75RCU,AEACU,AEACCU,TC75CL,TC75CU,
2
VRJCLM,RJCCU,R75FCL,R75RCU,AEACU,AEACCU,TC75CL,TC75CU,
3
VRJCLM,RJCCU,R75FCL,R75RCU,AEACU,AEACCU,TC75CL,TC75CU,
4
VRJCLM,RJCCU,R75FCL,R75RCU,AEACU,AEACCU,TC75CL,TC75CU,
5
VRJCLM,RJCCU,R75FCL,R75RCU,AEACU,AEACCU,TC75CL,TC75CU,
1
VRJCLM,RJCCU,R75FCL,R75RCU,AEACU,AEACCU,TC75CL,TC75CU,
2
VRJCLM,RJCCU,R75FCL,R75RCU,AEACU,AEACCU,TC75CL,TC75CU,
3
VRJCLM,RJCCU,R75FCL,R75RCU,AEACU,AEACCU,TC75CL,TC75CU,
4
VRJCLM,RJCCU,R75FCL,R75RCU,AEACU,AEACCU,TC75CL,TC75CU,
5
VRJCLM,RJCCU,R75FCL,R75RCU,AEACU,AEACCU,TC75CL,TC75CU,

CALCULATE SPEED OF ADVANCE

VA=V*(1.0-7.1)

CALCULATE UNCORRECTED REYNOLDS NUMBER AT 3/4 PROPELLER RADIUS

USING RELATION (101), REF 2

R75RUN=(1.0/WATNU)*C75R*SQR(T(VA++2)+1.75*PII*(N/60.0)*DI1**21)

DETERMINE BLADE THICKNESS-TO-CHORD RATIO BASED ON A SPECIFIC "Z" USING RELATION (11), REF 2

AEDVAC* USING RELATION (11), REF 2

TC75W=(G.185-0.00125*Z)+1/(12.073*AEDVAC)

DETERMINE REYNOLDS NUMER AT 3/4 RADIUS, CORRECTED FOR BLADE

THICKNESS-TO-CHORD RATIO "TC75W", USING RELATION (12), REF 2

APP21430

APP21440

APP21450

APP21460

APP21470

APP21480

APP21490

APP21500

APP21510

APP21520

APP21530

APP21540

APP21550

APP21560

APP21570

APP21580

APP21590

APP21600

APP21610

APP21620

APP21630

APP21640

APP21650

APP21660

APP21670

APP21680

APP21690

APP21700
NUM=1.0*(2.0*TC75WS)
DENOM=1.0*(2.0*TC75R1)
R75R=EXP(4.6052+SGRT(NUM/DENOM)+ALCG(R75RUN-4.6052))
RETLRN
ENC

APP2110
APP2120
APP2130
APP2140
APP2150

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SUBROUTINE RJCAL(J)

REAL*4 ETAQ,WEIGHT,AEDVAO,DIA,N,PE,POIVD,QS,TC75R,V,
1 RJCNL,RJCNJ,R75FCL,R75RCU,AEADCL,AEADCU,TC75CL,TC75CU,
2 PGWVL,DIACU,AEADCV,TCSTKS,RJ,
3 VK,IT,W,T,WATRO,WATNU,TEMN,NSCKW,HCL,PATH,
4 J
5 COMMON /GLOCXM/ETAC,WEIGHT,AEDVAO,DIA,N,PE,POIVD,QS,TC75R,V,RJCNL,
1 RJCNL,R75FCL,R75RCU,AEADCL,AEADCU,TC75CL,TC75CU,POW Bal,DIACU,
2 AEADCV,TCSTKS,RJ,
3 COMMON /PARH/VK,IT,W,T,WATRO,WATNU,TEMN,NSCKW,HCL,PATH,PATHVA,
1 PRCMAT,CIALHM,ETARR,AECMMN,TC75MN,SC

CALCULATE ADVANCE RATIO

J= (V*(1.0-W1))/((DIA*(N/60.0)))
RETURN
END
SUBROUTINE RNCALRN

SUBROUTINE: RNCAL

V
DIA
RJ
WT

fname
finput

DATE OF LAST REVISION: FEB 83
DEFINITION

V: VELOCITY (FT/SEC)
DIA: PROPELLER DIAMETER (FEET)
RJ: ADVANCE RATIO
WT: WAKE FRACTION
RN: PROPELLER REVOLUTION RATE (RPM)

REAL*4 ETAO,WEIGHT,AEDVAO,DIA,N,PE,POIVD,OS,TC75R,V,
RJCNU,RJCNU,R75FCL,R75RCU,AEADCL,AEALLU,TC75CL,TC75CU,
POMBAL,DIACNU,AEDCY,TCSTRS,RJ,
VK,TC,WT,2,WAIRG,WATNL,TEMP,NCSCRW,HCL,PATH,
P2,MAT,NCMAT,CIALIN,ETARK,AEACMN,TC75MN,SC,

COMMON /GLOECM/ETAO,WEIGHT,AEDVAO,DIA,N,PE,POIVD,OS,TC75R,V,KJCNU,
RJCNU,R75FCL,R75RCU,AEADCL,AEALLU,TC75CL,TC75CU,POMBAL,DIACNU,
AEDCY,TCSTRS,RJ,
COCOM/FRARH/VEK,TC,WT,2,WAIRG,WATNL,TEMP,NCSCRW,HCL,PATH,PNWAV,
P2,MAT,NCMAT,CIALIN,ETARK,AEACMN,TC75MN,SC

CALCULATE PROPELLER REVOLUTION RATE

RN=60*(V*(1.0-WT))/((DIA*RJ))
RETURN
END
| COMMON | /AREAL/ | BLADE SECTION AREAS (FEET**2) | APP26420 |
| COMMON | /VALI/ | ORIGINATE OF CRITICAL POINT NO. | APP26490 |
|         |       | 1 ON BLADE SECTION PERIPHERY | APP26500 |
|         |       | WITH RESPECT TO A SYSTEM OF Axes | APP26510 |
|         |       | PITCH-REFERENCE LINE WITH ORI- | APP26520 |
|         |       | GIN AT THE CENTROID OF THE | APP26530 |
|         |       | SECTION (FEET) | APP26540 |
| COMMON | /VAL2/ | ORIGINATE OF CRITICAL POINT NO. | APP26600 |
|         |       | 2 ON BLADE SECTION PERIPHERY | APP26610 |
|         |       | WITH RESPECT TO A SYSTEM OF Axes | APP26620 |
|         |       | PITCH-REFERENCE LINE WITH ORI- | APP26630 |
|         |       | GIN AT THE CENTROID OF THE | APP26640 |
|         |       | SECTION (FEET) | APP26650 |
| COMMON | /VAL3/ | ORIGINATE OF CRITICAL POINT NO. | APP26700 |
|         |       | 3 ON BLADE SECTION PERIPHERY | APP26710 |
|         |       | WITH RESPECT TO A SYSTEM OF Axes | APP26720 |
|         |       | PITCH-REFERENCE LINE WITH ORI- | APP26730 |
|         |       | GIN AT THE CENTROID OF THE | APP26740 |
|         |       | SECTION (FEET) | APP26750 |
| COMMON | /VAL4/ | ORIGINATE OF CRITICAL POINT NO. | APP26800 |
|         |       | 4 ON BLADE SECTION PERIPHERY | APP26810 |
|         |       | WITH RESPECT TO A SYSTEM OF Axes | APP26820 |
|         |       | PITCH-REFERENCE LINE WITH ORI- | APP26830 |
|         |       | GIN AT THE CENTROID OF THE | APP26840 |
CCCMON / STRES1/ DIRECT STRESS AT CRITICAL POINT 1 AT BLADE SECTIONS ALONG THE PROPELLER RADIUS (LBF/FT*2) APP23390

CCCMON / STRES2/ DIRECT STRESS AT CRITICAL POINT 2 AT BLADE SECTIONS ALONG THE PROPELLER RADIUS (LBF/FT*2) APP23420

CCCMON / STRES3/ DIRECT STRESS AT CRITICAL POINT 3 AT BLADE SECTIONS ALONG THE PROPELLER RADIUS (LBF/FT*2) APP23450

CCCMON / STRES4/ DIRECT STRESS AT CRITICAL POINT 4 AT BLADE SECTIONS ALONG THE PROPELLER RADIUS (LBF/FT*2) APP23490

REAL*4 AREA(10), RIXXNA(10), RIYYNA(10), L1(10), U2(10), U3(10), U4(10), W1(10), W2(10), W3(10), W4(10), EMPN(10), HNPL(10), CMCHBN(10), CMCHBL(10), BIGN(10)

REAL*4 SIGC(10), SIG1(10), SIG2(10), SIG3(10), SIG4(10)

INTEGER*4 IF

COMMON / AREELO/ AREA
COMMON / VAL1/ U1
COMMON / VAL2/ U2
COMMON / VAL3/ U3
COMMON / VAL4/ U4
COMMON / VAL5/ W1
COMMON / VAL6/ W2
COMMON / VAL7/ W3
COMMON / VAL8/ W4
COMMON / A2MCX/ RIYYNA
COMMON / A2MCY/ RIXXNA
COMMON / MRCNX/ EMPN
COMMON / MRCNY/ HNPL
COMMON / CMCHBN/ CMCHBL
COMMON / CMCHBL/ CMCHBN
COMMON / SIG0/ SIG1
COMMON / SIG1/ SIG2
COMMON / SIG2/ SIG3
COMMON / SIG3/ SIG4

CALCULATE DIRECT STRESS (LBF/FT*2) DUE TO CENTRIFUGAL FORCE FOR BLADE SECTIONS ALONG THE PROPELLER RADIUS

DO 1 IR=2,9
   SIGC(IR)=BIGN(IR)/AREA(IR)

1  CONTINUE
1 CONTINUE
CALCULATE TOTAL BENDING MOMENT COMPONENT (FT-LB) PARALLEL TO
PITCH REFERENCE (CG-CD) LINE, IMPOSED BY HYDRODYNAMIC AND
CENTRIFUGAL LOADING
DO 2 IR=2,9
TCTBML(IR)=HMPL(IR)+CMGBL(IR)
2 CONTINUE
CALCULATE TOTAL BENDING MOMENT COMPONENT (FT-LB) NORMAL TO
PITCH REFERENCE (CG-CD) LINE, IMPOSED BY HYDRODYNAMIC AND
CENTRIFUGAL LOADING
DO 2 IR=2,9
TCTEML(IR)=HMPL(IR)+CMGBL(IR)
3 CONTINUE
CALCULATE STRESSES (LBF/FT**2) AT CRITICAL POINTS 1, 2, 3 AND 4
ALONG THE PROPELLER RADIUS USING RELATION (105), REF 8, WHERE...
SIG1(IR) DIRECT STRESS AT CRITICAL POINT 1 SPECIFIED BY
BLADE SECTION COORDINATES (W1, U1)
SIG2(IR) DIRECT STRESS AT CRITICAL POINT 2 SPECIFIED BY
BLADE SECTION COORDINATES (W2, U2)
SIG3(IR) DIRECT STRESS AT CRITICAL POINT 3 SPECIFIED BY
BLADE SECTION COORDINATES (W3, U3)
SIG4(IR) DIRECT STRESS AT CRITICAL POINT 4 SPECIFIED BY
BLADE SECTION COORDINATES (W4, U4)
DO 4 IR=2,9
SIG1(IR)=SIGCF(IR)*((TUBML(IR)*(-W1(IR)))/K1YNA(IR))
SIG2(IR)=SIGCF(IR)*((TUBML(IR)*(-L1(IR)))/K1YNA(IR))
SIG3(IR)=SIGCF(IR)*((TUBML(IR)*(-L3(IR)))/K1YNA(IR))
SIG4(IR)=SIGCF(IR)*((TUBML(IR)*(-L4(IR)))/K1YNA(IR))
4 CONTINUE
RETURN
END
SUBROUTINE STRck(SEC, C79, SCSTKS)

INPUT            OUTPUT

P1MAT           PROPELLER MATERIAL IDENTIFIER
F1: CAST IRON
F2: CAST STEEL
F3: TYPE 2 BRONZE
F4: TYPE 4 Ni-AL BRONZE
F5: STAINLESS STEEL

DIA
N
PD1VD
K
C79R
NOSCR
TC79R

SCSTKS

REAL*4 ETA0, WEIAT, AEOVAD, DIA, NPE, PD1VC, VT, C79R, V,
1 RJCNL, RJCNU, R75LCl, R75CLC, AEOACL, AEALCU, TC79CL, TC79CU,
2 FCB0L, DIA0L, AEALCV, TCSTKS, RJ,
3 V0, TC, WT, 2, WATRC, WATNM, WATEC, NOSCRW, HCL, PATHM,
4 PWM, P1C, P1MAT, DIALIP, ETAM, AEALCM, TC75MN, SCSTKS,
5 C79R, KQ, PI1, SC, LADC, PB, S, PADC, FAD2, FAD3, 175MIN
COMMON /GLOCEO/ETA0, WEIGHT, AEOVAD, DIA, NPE, PD1VD, VS, C79R, V, RJCNL,
1 R75LCL, R75CLC, AEOACL, AEALCU, TC79CL, TC79CU, PDWBAL, DIA0L,
2 AEALCV, SCSTKS, RJ
COMMON /FAR0M/VT, TC, WT, WATKU, WATNM, TMP, NOSCRW, HCL, PATHM, WATVA,
1 PROMAT, LC, ETA0, AEALDN, TC75MN, SC
PI1=3.14159265

DETERMINE MAXIMUM ALLOWABLE STRESS (PSI) BASED ON NUMBER OF PRO-
PELLERS AND MATERIAL IDENTIFIER

IF (.NOT. (.LE. NOSCR, EQ. 1.0)) GO TO 1
   IF (P1MAT, EQ. 1.0) SC=3600.0
   IF (P1MAT, EQ. 2.0) SC=5500.0
   IF (P1MAT, EQ. 3.0) SC=7200.0
   IF (P1MAT, EQ. 4.0) SC=8510.0
   IF (P1MAT, EQ. 5.0) SC=5400.0
GO TO 2
1 CONTINUE
   IF (P1MAT, EQ. 1.0) SC=3500.0
   IF (P1MAT, EQ. 2.0) SC=6265.0

APP24300
APP24310
APP24320
APP24330
APP24400
APP24410
APP24420
APP24430
APP24440
APP24450
APP24460
APP24470
APP24480
APP24490
APP24500
APP24510
APP24520
APP24530
APP24540
APP24550
APP24560
APP24570
APP24580
APP24590
APP24600
APP24610
APP24620
APP24630
APP24640
APP24650
APP24660
APP24670
APP24680
APP24690
APP24700
APP24710
APP24720
APP24730
APP24740
APP24750
APP24760
APP24770
IF (PROPAT .EQ. 3.0) SC = 7985.0
IF (PROPAT .EQ. 6.0) SC = 9430.0
IF (PROPAT .EQ. 3.0) SC = 5900.0

2 CONTINUE

DETERMINE ABSORBED POWER FOR EACH PROPELLER

WABSRB = AEX(KQ * WATRC * (DIA**5) * (((W/60.0)**2))
PAEBRB = (2.0*PI*QABSRB*N)/33000.0

CALCULATE MINIMUM REQUIRED BLADE THICKNESS-TO-CHORD RATIO AT 3/4
BLADE RADIUS USING RELATION (16), REF 2

FAC1D = SC + (((DIA**N)**2)/(12.7881))
FAC2D = 4.1234*10**(N/(CIA**3))
FAC3D = (2.375*C-12.25)*PUIVDI*PABSRE
T75MN = (((FAC1D/(FAC2D*(FAC1D)**2)*0.333331**0.2111+0.00281*DIA
TC75MN = T75MN/TC75R

DETERMINE CONSTRAINT VARIABLE FOR BLADE THICKNESS-TO-CHORD RATIO

CONSTRAINT

SCSTRS = (TC75MN/TC75R)-1.0
RETURN
END
SUBROUTINE STRCNK(K4,KT,C75R,SCSTRS)

SUBROUTINE: STRCNK

CATE OF LAST REVISION: APR 83

INPUT OUTPUT

FACMAT PROPELLER MATERIAL IDENTIFIER

1: CAST IRON
2: CAST STEEL
3: TYPE 3 NI-AL BRONZE
4: STAINLESS STEEL
5: TRACING BRONZE

DIA PROPELLER DIAMETER (FT)

PDIVD PROPELLER REVOLUTION RATE (RPM)

AEVAD EXPANDED AREA RATIO

Q0 THRUST COEFFICIENT

K0 THRUST COEFFICIENT

C75R CHORD LENGTH 3/4 RADIUS (FT)

NO. OF PROPELLERS

ELACE THICKNESS-TO-CHORD RATIO

3/4 RADIALS

CONSTRAINT VARIABLE FOR BLADE

THICKNESS-TO-CHORD RATIO 3/4

SCSTRS

REAL*4 ETAQ,WEIGHT,AEVAD,DIA,K,PE,PDIVD,QS,C75R,Kd

RJCNLRJCNR,R75RCL,R75RCU,AEACL,AEACCU,C75CL,C75CU,

5

VK,TC,WT,2,KTRE,MATNU,TEMP,SCSTRS,HCL,ATM,

4

FJAT4,FACMAT,DIALIM,FARK,

5

P,J,C75R,K75R,KJ

REAL*4 TOUR,T1XR,T2OR,T3OR,T4OR,T5OR,T6GR,T7OR,T8OR,T9OR,

1

1205.F,RT

1

REAL*4 CR(10),AR(10),BR(10),PLF(10),PLA(10),TR(10),VF(10,11),

1

V2F(10,11),V1A(10,10),V2A(10,10),VFACE(11),VFACE(11),

2

V5F(10,11),V1F(11),DPEA110,DA110,DFSA110,DA110,DA110,

2

SAMXX,SMAYA,SPA2A,SMAYA,SPA2A,STEMPS,

5

FPEF(11),V5F(11),VF5F(11),VF5F(11),VF5F(11),VF5F(11),

5

SMAXF,SMAXF,SUMAF,SMAXF,SMAXF,SMAXF,SMAXF,

1

R110100,SMAXF,SMAXF,SMAXF,SMAXF,SMAXF,SMAXF,

1

REAL*4 U11100,021110,031110,041110,051110,061110,0711110

1

SCSTRS

1

INTEGER IN0,KJCNK

LOGICAL CKAY1,OKAY2,OKAY3,CKAY4

COMMON /GLOESC/ETAQ,WEIGHT,AEVAD,DIA,K,PE,PDIVD,QS,C75R,KJCNLRJCNR,R75RCL,R75RCU,AEACL,AEACCU,C75CL,C75CU,POMBAL,CJACNU

APP25450

APP25460

APP25470

APP25480

APP25490

APP25500

APP25510

APP25520
Determine maximum allowable stress (PSI) based upon the number of propellers and type of material.

IF(1-NOT((NO5CMN.EQ.1.0)) GO TO 1
   IF((PROFAT.EQ.2.0).AND.(SC=3600.0)) GOTO 2
   IF((PROFAT.EQ.3.0).AND.(SC=7200.0)) GOTO 2
   IF((PROFAT.EQ.4.0).AND.(SC=8900.0)) GOTO 2
   IF((PROFAT.EQ.5.0).AND.(SC=5400.0)) GOTO 2
GO TO 2
1 CONTINUE
   IF((PROFAT.EQ.1.0).AND.(SC=3550.0)) GOTO 2
   IF((PROFAT.EQ.2.0).AND.(SC=6265.0)) GOTO 2
   IF((PROFAT.EQ.3.0).AND.(SC=7585.0)) GOTO 2
   IF((PROFAT.EQ.4.0).AND.(SC=9430.0)) GOTO 2
   IF((PROFAT.EQ.5.0).AND.(SC=9500.0)) GOTO 2
2 CONTINUE

Initialize minimum required blade thickness-to-chord ratio at 3/4.
PROPPELLER RADIUS TO A PERCENTAGE OF THE RATIO FOR THE SERIES

PROPELLER USING RELATION (11), REF 2

TC75MN = (10.0185-10.00125*Z11)+1/12.073*AEVAC

ITERATE FOR MINIMUM REQUIRED BLADE THICKNESS-TO-CHORD RATIO AT 3/4

PROPPELLER RADIUS BASED UPON THE CRITERIA THAT THE DIRECT STRESSES
CALCULATED AT CRITICAL POINTS 1 (W1,U1), 2 (W2,U2), 3 (W3,U3) AND 4
(4A,4A) DO NOT EXCEED THE MAXIMUM ALLOWABLE STRESS AS PREVIOUSLY
DETERMINED. ITERATE FOR A MAXIMUM OF 10C ITHERS.

KOUNT=C

3 CONTINUE

TC75MN = TC75MN+0.0010

KCOUNT = KCOUNT+1

CALCULATE MAXIMUM BLADE SECTION THICKNESS DISTRIBUTION ALONG
THE PROPPELLER RADIUS

CALL TC75R,TC75MN,DIA,Z,AEVAC

DETERMINE ELACE SECTION PROPERTIES

CALL BLDPRP

DETERMINE BENDING MOMENTS DUE TO HYDRODYNAMIC LOADING

CALL HYDOLKU,K1

DETERMINE FORCE AND BENDING MOMENTS DUE TO CENTRIFUGAL
LOADING

CALL CFGLC

DETERMINE STRESS (LBF/FT2) AT CRITICAL POINTS 1,2,3,4

CALL SIGNS

INITIALIZE LOGICAL VARIABLES FOR CURRENT ITERATION

CKAY1=TRUE
CKAY2=TRUE
CKAY3=TRUE
CKAY4=TRUE

CHECK STRESSES AT CRITICAL POINTS 1,2,3, AND 4 TO DETERMINE
WHETHER OR NOT MAXIMUM ALLOWABLE STRESS IS EXCEEDED

APP26010
APP26020
APP26030
APP26040
APP26050
APP26060
APP26070
APP26080
APP26090
APP26100
APP26110
APP26120
APP26130
APP26140
APP26150
APP26160
APP26170
APP26180
APP26190
APP26200
APP26210
APP26220
APP26230
APP26240
APP26250
APP26260
APP26270
APP26280
APP26290
APP26300
APP26310
APP26320
APP26330
APP26340
APP26350
APP26360
APP26370
APP26380
APP26390
APP26400
APP26410
APP26420
APP26430
APP26440
APP26450
APP26460
APP26470
APP26480
DC 8 IF=2,5
  IF NOT ABS(SIG1(IR)) GE (SC*144.0) GO TO 4
  CKAY1=.FALSE.
  CONTINUE
4  IF NOT ABS(SIG2(IR)) GE (SC*144.0) GO TO 5
  CKAY2=.FALSE.
  CONTINUE
5  IF NOT ABS(SIG3(IR)) GE (SC*144.0) GO TO 6
  CKAY3=.FALSE.
  CONTINUE
6  IF NOT ABS(SIG4(IR)) GE (SC*144.0) GO TO 7
  CKAY4=.FALSE.
  CONTINUE
7  IF NOT (OKAY1).AND.(CKAY2).AND.(OKAY3).AND.(OKAY4) GC TO 3
8  IF NOT (((CKAY1).AND.(OKAY2).AND.(CKAY3).AND.(OKAY4)) OR.
  (KCONT.EQ.100)) GC TO 3

STRESSES AT 3/4 PROPELLER RADIUS, CALCULATE CONSTRUCTION VARIABLE
STRESSES = TC75MN / TC75R = 1.0
RETURN
END
SUBROUTINE 1DIST (C75, TC75, DIA, Z, AEDVAC)

SUBROUTINE: TOIST

DATE OF LAST REVISION: MAR 83

INPUT

GLTPUT

C75

TC75

DIA

ALEVAC

CCMCMN /THICD/

REAL*4 TOOR, T1XR, T2OR, T3OR, T49R, T5OR, T6OR, T7OR, T8OR, T9OR

COMMON /THICD/, TOOR, T1XR, T2OR, T3OR, T49R, T5OR, T6OR, T7OR, T8OR, T9OR, T1CR, FAT

CALCULATE MAXIMUM THICKNESS AT 3/4 RADIUS

T75R = TC75R * C75R

CALCULATE MAXIMUM THICKNESS AT 3/4 RADIUS FOR SERIES PROPELLER USING RELATION (11), REF 2

T75RS = DIA *( 0.0185 - ( 0.00125 * Z ) )

CALCULATE RATIO OF MAXIMUM THICKNESSES AT 3/4 RADIUS

KAT = T75R / T75RS

GENERATE A DISTRIBUTION OF BLADE SECTION MAXIMUM THICKNESSES ALONG THE PROPELLER RADIUS BASED ON THE RATIO CALCULATED ABOVE

IF (L3) (2. 3. 0. 1) GO TO 1

C3

TOOR = 0.050 * DIA

T1XR = R/DIA *( 0.05304 - ( 0.00412 ) )

GO TO 5

1 CONTINUE

IF (L3) (2. 4. 0. 1) GO TO 2

C3

TOOR = 0.045 * DIA

T1XR = R/DIA *( 0.05406 - ( 0.00416 ) )

GO TO 3

2 CONTINUE
IF (NOT (2.4Q.5.3)) GO TO 3
TCCR=0.040*DA
TJR=RAT*DA* (0.054646-0.0041e5*Z)
GO TO 5
3 CONTINUE
IF (NOT (2.4Q.6)) GO TO 4
TCCR=0.035*DA
TJR=RAT*DA* (0.054646-0.0041e5*Z)
GO TO 5
4 CONTINUE
TCCR=0.035*DA
TJR=RAT*DA* (0.05384-0.0041e5*Z)
5 CONTINUE
T20=RAT*DA* (0.0016-0.0040*Z)
T30=RAT*DA* (0.0050-0.0035*Z)
T40=RAT*DA* (0.0002-0.0030*Z)
T50=RAT*DA* (0.0003-0.0025*Z)
T60=RAT*DA* (0.0040-0.0020*Z)
T70=RAT*DA* (0.0025-0.0015*Z)
T80=RAT*DA* (0.0015-0.0010*Z)
T90=RAT*DA* (0.0005-0.0005*Z)
T100=RAT*DA* (0.0030-0.0000*Z)
RETURN
END
COMMON /CR0/LNT/CR
COMMON /VALL1/X1
COMMON /VALL2/X2
COMMON /VALL3/X3
COMMON /VALL4/X4
COMMON /VALL1/X1
COMMON /VALL2/X2
COMMON /VALL3/X3
COMMON /VALL4/X4
COMMON /A2MCMY/R1YAA
COMMON /A2MCMY/R1XNA

Determine blade section maximum thickness distribution
CALL TC1ST(75R,TC75R,DIA,Z,AE/VAC)

Determine blade section properties
CALL BLCFRP

Determine volume of a propeller blade
CALL BLCBR(VOLELD)

Specify weight censity of material selected where...

<table>
<thead>
<tr>
<th>PROMAT</th>
<th>MATERIAL</th>
<th>WEIGHT CENSIETY (Lb/Ft*In**3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>CAST IRON</td>
<td>.260</td>
</tr>
<tr>
<td>2</td>
<td>CAST STEEL</td>
<td>.284</td>
</tr>
<tr>
<td>3</td>
<td>TYPE 2 BRONZE</td>
<td>.305</td>
</tr>
<tr>
<td>4</td>
<td>TYPE 4 NI-AL BRONZE</td>
<td>.278</td>
</tr>
<tr>
<td>5</td>
<td>STAINLESS STEEL</td>
<td>.283</td>
</tr>
</tbody>
</table>

IF (PROMAT.EC.1.CMWC = .260)
IF (PROMAT.EC.2.CMWC = .284)
IF (PROMAT.EC.3.CMWC = .305)
IF (PROMAT.EC.4.CMWC = .278)
IF (PROMAT.EC.5.CMWC = .283)

Calculate propeller blade weight
WEIGHT = CLBLD*WC*(1728.0)
RETURN
END
SUBROUTINE ANALIZ(ICALC)
INTEGER*4 I CALC
REAL*4 ETAQ, HEIGHT, ADYVAG, DIA, N, PE, PDIVD, QS, TC755R, V,
! 1 ! RJCNU, R755C, R755G, AEAQCL, AEAGCU, TC75CL, TC755U,
! 2 ! FNOMAL, DIAHAN, AEAQVY, CTSTAS, RJ,
! 3 ! VK, IE, WT, 2, NATH, MAINU, TEMP, NCSCRM, HCL, PATM,
! 4 ! PHATVA, PROMAT, DIALIN, ETARR, AEQMN, TC75MN, SC,
! 5 ! C35R, R755K, KE, PD
COMMON /GLODCM/ETAQ, HEIGHT, ADYVAG, DIA, N, PE, PDIVD, QS, TC755R, V, RJCNU,
1RJCNL, R755C, R755G, AEAQCL, AEAGCU, TC75CL, TC755U, PUNBAL, DIAHAN,
2AEACLV, TCSM, RJ,
COMMON /PARAM/VK, IE, WT, 2, NATH, MAINU, TEMP, NCSCRM, HCL, PATM, PHATVA,
1PROMAT, DIALIN, ETARR, AEAQMN, TC75MN, SC

THIS SUBROUTINE IS COUPLED WITH COPES/COMMON CONSTITUTES ANALYSIS
METHOD FOR "DESIGN CASE 1" PROPELLER SELECTION PROBLEMS

INPUT-INITIALIZATION PHASE

PII=3.14159264
IF (NOT.(ICALC.EQ.1)) G0 TO 1

SET "DESIGN CASE 1" PARAMETERS

ENVIRONMENTAL

TEMP=55.0
WATST=1.9364
MAINU=0.000122850
PATM=14.7
PHATVA=.247

PROPELLER PARAMETERS

Z=6.0
PROMAT=5.0

HLLL PARAMETERS

WT=022
IE=01
ETARR=1.025
NCSCRM=1.0
HCL=19.0
DIALIN=22.0

SET DESIGN VARIABLES HELD FIXED FOR "DESIGN CASE 1"

APPCC010
APPCC020
APPCC030
APPCC040
APPCC050
APPCC060
APPCC070
APPCC080
APPCC090
APPCC100
APPCC110
APPCC120
APPCC130
APPCC140
APPCC150
APPCC160
APPCC170
APPCC180
APPCC190
APPCC200
APPCC210
APPCC220
APPCC230
APPCC240
APPCC250
APPCC260
APPCC270
APPCC280
APPCC290
APPCC300
APPCC310
APPCC320
APPCC330
APPCC340
APPCC350
APPCC360
APPCC370
APPCC380
APPCC390
APPCC400
APPCC410
APPCC420
APPCC430
APPCC440
APPCC450
APPCC460
APPCC470
APPCC480
PE=181.530
VK=24.6
V=1.688*VK
AEEl=3.85
DIA=22.0
TC75R=(L.0185-0.5125*21+1/12.073*AEEl)

END OF INPLT-INITIALIZATION PHASE

GO TO 2

EXECUTION PHASE

1 CONTINUE
IF (.NOT.(I.EQ.2)) GC TO 2
CALL RACAL(N)
CALL G175R(I,C75K)
CALL R175R(I,C75R)
CALL CEPSA(RJ,R75K,KT,KQ)
CALL OWEFF(RJ,KT,KQ,ETAD)
CALL CALQSIKC,QS)
CALL JCNO(RJ,R75K,RCNU)
CALL EXPGN(I,AEEl,C75K,AEALL,AEACU,TC75CL,TC75CU)
CALL BLPW(IK,T,PUBAL)
CALL DIGNUA(I,HCNU)
CALL CAVLNAKI,AEACU)
CALL STACNKIC,C75K,TCSTRS)

END OF EXECUTION PHASE

GO TO 3

2 CONTINUE

OUTPUT-RESULT PHASE

PC=12.*PI1*QS*N1/33000.0
WRITE(*,90000)
WRITE(*,90001)
WRITE(*,90002,111,90000,111,90001)
WRITE(*,90003)111,111,90000,111,90001
IF (.NOT.(I.EQ.1)) GC TO 81
WRITE(*,90005)

CONTINUE

IF (.NOT.(I.EQ.2)) GC TO 82
WRITE(*,50085)

CONTINUE

IF (.NOT.(I.EQ.2)) GC TO 83
WRITE(*,50086)
11X,25X, ALLICABLE STRESS (PSI) * KX, * F10.4,  / /, APP01450
9005 FORMAT (IX,25X, MATERIAL TYPE,2IX, *= **STAINLESS STEEL**, ,APP01460
9010 FORMAT (IX,25X, MATERIAL TYPE,2IX, *= NCT CONSIDERED**, ,APP01480
9011 FORMAT (IX, *ELEETICA VALUES:*,12X,*PE (FP),27X, *= **F10.4**, ,APP01490
8 11X,25X, KG * KX, *= **F10.4**, ,APP01560
10 11X,25X, REY75R * KX, *= **F10.4**, ,APP01580
14 11X,25X, 7C .75R * KX, *= **F10.4**, ,APP01620
END
SUBROUTINE ANALYLCALC
INTEGER*4 ICALC
REAL*4 ETA0,WEIGHT,AEDVAM,DIAM,P,W,FLUVE,US,TC75R,V,
       R,JCJN.R,JCJNC.R,TC75CU.AEACCU,TC75CL.TC75SU,
       FCWAL,DICNU.AEACCU.TCACTN,RJ;
COMMON /GDCM/ETA0,WEIGHT,AEDVAM,DIAM,P,W,FLUVE,US,TC75R,V,JCJN.
1R,JCJNC.R,TC75CU.AEACCU,TC75CL.TC75SU,FCWAL,DICNU.RJ
2/COMMON ,PARAM/VC,TC,W,T,ATU,W,ATNU,TEMP,NCSCRW,HCL,PATI,M,WATVA,
1PRCMA,T,LIALIM,ETARR,AEACCM,TC75MN,SC
C
C THIS SUBROUTINE, COUPLED WITH CUDES/CONIN, CONSTITUTES ANALYSIS
C METHOD FOR "DESIGN CASE I" PROPELLER SELECTION PROBLEMS
C
C INPLT-INITIALIZATION PHASE
C
PI1=3.14159264
IF (.NOT. ILCALC.EQ. 1116C TO 1
C
SET "DESIGN CASE I" PARAMETERS
C
ENVIRONMENTAL
TEPP=95.0
WATRO=1.9384
WATNC=0.000122850
PATI=14.7
WATVA=.247
C
PRCPELLE R PARAMETERS
Z=2.6
PRCMA,T=5.0
C
HULL PARAMETERS
HT=6.25
TC=.15
ETARR=1.025
NCSCRW=1.0
HCL=19.0
DIALIM=22.0
C
SET DESIGN VARIABLES FIELD FIXED FOR "DESIGN CASE I"
C
PE=16153.0
VK=24.0
V=1.486*VK
AEVALQ=0.85
DIA=22.0
TC75=110.0185-0.0125*Z1*Z1/(2.073*AEVALQ)

GO TO 3

EXECUTION PHASE

1 CONTINUE
IF (.NOT. (ICALC.EQ.211) GC TO 2
CALL RICALN
CALL C7SRAC(75R)
CALL REY5R(C175R,R75R)
CALL CCEFSA(RJ,R75R,KT,KQ)
CALL FMWFF(RJ,KT,KQ,ETAJ)
CALL CALCSKQ(DSI)
CALL JCNAR(RJ,RJCNL,JCNUL)
CALL REYCNAR(R75R,R75RCL,R75RCU)
CALL EXTCCNZ(5,AECAV),TC75R,AEACL,AEACU,TC75CL,TC75CU)
CALL BIPOL(1),PONBAL)
CALL DACNAR(RJ,DIACLJ)
CALL CAVCNAR(KT,AEACV)
CALL STACNK(5,KT,C75R,TC7S)

GO TO 2

2 CONTINUE

OUTPUT-RESULT PHASE

PC=(2.0*PI1*QS*N1/33000.0
WRITE(6,9000)
WRITE(6,9001)
WRITE(6,9002)TEMP,RAWR,RAWR,RAWK,PHATVA
WRITE(6,9003)TW,ETARR,HOSCK,HCL,DIALIM
WRITE(6,9004)
IF (.NOT. (ICM1.EQ.1) GC TO 61
WRITE(6,9005)SC
GO TO 66
CONTINUE
IF (.NOT. (ICM1.EQ.2) GC TO 62
WRITE(6,9006)SC
221

CC CONTINUE
82 GC IC 66
   IF*NOI,(PROMAT,EG)=0.0166 TO 83
      WRITE(6,S90715C)
      APP02650
   ELSE
      APP02690
   END IF
     APP02660
   GC IC 66
   CONTINUE
   IF*NCI,(PROMAT,EG)=0.0166 TO 84
      WRITE(6,S90815C)
      APP02700
   ELSE
      APP02740
   END IF
     APP02780
   GC IC 66
   CONTINUE
   IF*NOI,(PROMAT,EG)=0.0166 TO 85
      WRITE(6,S90915C)
      APP02830
   END IF
     APP02870
   GC IC 66
   CONTINUE
   IF*NCI,(PROMAT,EG)=0.0166 TO 86
      WRITE(6,90110PE,VE,US,PD,RJ,KK,KC,ETAC,R75R,DIA,PLIVD,
      AEOVAL,TC75R
      1 WRITE(6,90120DIALIM,AEOAM,TC75MN
      3 CONTINUE
      RETURN
CCC MISCELLANEOUS FORMAT STATEMENTS
9000 FORMAT(*10,E11.6,3x,'OPTIMIZATION RESULTS -------- DESIGN CASE NO. 1*','/
      APP02890
      10x,/* SUBROUTINE "STBNCH"*/)
9001 FORMAT(*100x,'ENVIRONMENTAL PARAMETERS: PE, V, AEOMAC, DIA, TC75R*/)
9002 FORMAT(*100x,'TEMP (DEG F)*, 2X, =*
      APP02950
      1 *F 10.4*,/
      APP02930
      10 'C000',/ 10 'C009',/
      APP02930
      10 x=12X,/*,F10.4*/,/
      APP02970
      10 x=12X,/*,F10.4*/,/
      APP02990
      10 x=12X,/*,F10.4*/,/
      APP03000
      10 x=12X,/*,F10.4*/,/
      APP03020
      10 x=12X,/*,F10.4*/,/
      APP03040
      10 x=12X,/*,F10.4*/,/
      APP03060
      10 x=12X,/*,F10.4*/,/
      APP03080
      10 x=12X,/*,F10.4*/,/
      APP03100
      10 x=12X,/*,F10.4*/,/
      APP03120
      10 x=12X,/*,F10.4*/,/
      APP03140

L
9005 FORMAT: IX, 25X, "ALLCABLE STRESS (PSI)", J2X, '=', F10.1, '/
9010 FORMAT: IX, 25X, "STAINLESS STEEL",
2 1X, 25X, 'V (FT/SEC)', 23X, '=', F10.4, '/
3 1X, 25X, 'K (RPM)', 23X, '=', F10.4, '/
4 1X, 25X, 'CS (FT-LBF)', 23X, '=', F10.4, '/
5 1X, 25X, 'PD (HP)', 23X, '=', F10.4, '/
6 1X, 25X, 'J', 23X, '=', F10.4, '/
7 1X, 25X, 'K', 23X, '=', F10.4, '/
8 1X, 25X, 'ETA', 23X, '=', F10.4, '/
9 1X, 25X, 'REY75K', 23X, '=', F10.4, '/
10 1X, 25X, 'DIA (FT)', 23X, '=', F10.4, '/
11 1X, 25X, 'F/D', 23X, '=', F10.4, '/
12 1X, 25X, 'AE/AC', 23X, '=', F10.4, '/
13 1X, 25X, 'T/C', 23X, '=', F10.8, '/
9012 FORMAT: IX, 'CONSTRAINT VALUES:', 11X, 'MAX DIA (FT)', 22X, '=', F10.4, '/
1 1X, 25X, 'PE (IPJ), 27X, '=', F10.1, '/
2 1X, 25X, 'ETA', 23X, '=', F10.4, '/
ENG
SUBROUTINE ANALIZICALC
INTEGER I, ICALC
REAL*4 ETAG, WEIGHT, AECLAV, CIA, PE, FDIVC, QS, TC75R, V,
1 R, JCNW, JCNV, R75RCL, R75RCU, AEACCL, AEACCU, TC75CL, TC75CU,
2 FOWCL, DIACNU, AEACCV, TCSTAS, RJ,
3 TK, ITC, MT, Z, WATRC, WATNU, TEM, NCSTRM, HCL, PATM,
4 PNTA, PROMAT, DIAMET, ETA, AK, AEACMN, TC75MN, SC,
5 C75R, R75R, KT, KC, PD
COMMON /GLOECM/ETAG, WEIGHT, AECLAV, DIA, N, PE, FDIVC, QS, TC75R, V, RJCNL,
1 RJCNU, R75RCL, R75RCU, AEACCL, AEACCU, TC75CL, TC75CU, POWBAL, DIACNU,
2 AEACCV, TCSTAS, RJ
COMMON /PARAM/TK, ITC, MT, Z, WATRC, WATNU, TEM, NCSTRM, HCL, PATM, PNTA,
1 PRCMAT, DIAMET, ETA, AK, AEACMN, TC75MN, SC

CC THIS SUBROUTINE, COUPLED WITH GPES/CONMIN, CONSTITUTES ANALYSIS
CC METHOD FOR "DESIGN CASE 1" PROPELLER SELECTION PROBLEMS
CC INPUT - INITIALIZATION PHASE
II=3,141592656
IF (.NOT. I(CALC.EQ.1)) GOTO 1

CC SET "DESIGN CASE 1" PARAMETERS
CC ENVIRONMENTAL
TEMP=55.0
WATRC=1.9384
WATNU=.000612285
PATM=14.7
PNTA=.247
CC PROPPELLER PARAMETERS
Z=5.0
PRCMAT=5.0
CC HULL PARAMETERS
L=6.22
TC=0.15
ETARR=1.025
NCSTRM=1.0
HCL=19.0
DIAMET=22.0
CC SET DESIGN VARIABLES HELD FIXED FOR "DESIGN CASE 1"
CC
PE=18153.0
VK=2.6E
V=1.28*VK

END OF INPUT-INITIALIZATION PHASE

GO TO 3

EXECUTION PHASE

1 CONTINUE

IFI .NOT. (ICALC, EQ. 2) GO TO 2

CALL RACAI(N)
CALL C75RAIC(75K)
CALL R75RIC(75K, R75R)
CALL C75FSAIR(J, K, 75K, K1, KU1)
CALL DFWEFFIR(J, K, KQ, ETAQ)
CALL C2LC5S1KC(QS)
CALL JCNATJR(JRCAL, RJENU)
CALL REYCNAR75K, R75RCL, R75K(CU)
CALL EXINC12Z, AEVAD, TC75K, AEACL, AEACU, TC75CL, TC75CU1
CALL B1PIWJ1K1, POJBAL)
CALL D1CNVA1D, IACNU)
CALL C1VCA1K1, 1AEACL)
CALL STACNAIKG, C75K, TC75K)

END OF EXECUTION PHASE

GO TO 3

2 CONTINUE

OUTPUT-RESULT PHASE

PE=12. (AP)10US*N)/33000.0
WRITE(6, 90000)
WRITE(6, 90001)
WRITE(6, 90002) TEMP, WATRU, WATNU, PATM, PRATVM
WRITE(6, 90003) I1, ID, ETARK, NUSCREN, HCL, DIAXI
WRITE(6, 90004)
IFL, NOT. (PROMAT EC1, 01) GC TO E1
WRITE(6, 90005) SC
GC TO EC
CENTINUE

81
IFL. (CAL1 (PROMAT EC 2, 011) GC TO E2
WRITE(6, 50001) SC
GC TO EC
CENTINUE

82
IFL. NOT. (PROMAT EC 3, 011) GC TO E3
WRITE(6, 50002) SC
GC TO EC
CENTINUE

APP03800
APP03810
APP03820
APP03830
APP03840
APP03850
APP03860
APP03870
APP03880
APP03890
APP038A0
APP038B0
APP038C0
APP038D0
APP038E0
APP038F0
APP04010
APP04020
APP04030
APP04040
APP04050
APP04060
APP04070
APP04080
APP04090
APP040A0
APP040B0
APP040C0
APP040D0
APP040E0
APP040F0
APP04100
APP04110
APP04120
APP04130
APP04140
APP04150
APP04160
APP04170
APP04180
APP04190
APP041A0
APP041B0
APP041C0
APP041D0
APP041E0
APP041F0
APP04200
APP04210
APP04220
APP04230
APP04240
APP04250
APP04260
APP04270
APP04280
APP04290
APP042A0
APP042B0
APP042C0
APP042D0
APP042E0
APP042F0
APP04300
APP04310
APP04320
SUBROUTINE ANALIZE I CALC
INTEGER*4 ICALC
REAL*4 ETA0,WEIGHT,AEDVAU,DIA,NPE,PDIVD,QS,TC75K,V
FJCNL,JCNJ,R75CL,R75RCU,AEACL,AEACCU,TC75CL,TC75CU,
V
FCWBL,DIAJNU,AEADCV,TCSTRS,RJ
VK,TC,W1,W2,WAIRG,WATNU,TMPP,NCSCRW,HLCL,PATM,
FMAT,J,DIALIM,ETARK,AEACMN,TC75MN,SC,
COMMON /GLOCNM/ETA0,WEIGHT,AEDVAU,DIA,NPE,PDIVD,QS,TC75K,V,RCJNL
1JRJCNJ,R75CL,R75RCU,AEACL,AEACCU,TC75CL,TC75CU,PUWBL,DIAJNU,
2AEACCV,TCSTRS,RJ
COMMON /PARAM/VK,TE,W1,W2,WAIRG,WATNU,TMPP,NCSCRW,HLCL,PATM,PWATVA,
1PRCMAT,DIALIM,ETARK,AEACMN,TC75MN,SC

C
C THIS SUBROUTINE COUPLED WITH COGES/COMIN CONSTITUTES ANALYSIS
C METHOD FOR "DESIGN CASE 1" PROPELLER SELECTION PROBLEMS
C
C INP0-INITIALIZATION PHASE
C
PI=3.14159265
C
IF(1).NE.IICALC.EQ.1)GO TO 1
C
SET "DESIGN CASE 1" PARAMETERS
C
ENVIROMENTAL
C
TEMF=55.0
WATRG=1.9364
WATNU=.0000012265
PATM=14.7
PWTVA=.247
C
PR0PELLER PARAMETERS
C
Z=.50
PRCMAT=.50
C
HULL PARAMETERS
C
W1=.24
T1=.10
ETARK=1.025
NCSCRW=1.0
HLCL=19.0
DIALIM=22.0
C
SET DESIGN VARIABLES HELD FIXED FOR "DESIGN CASE 1"
C
APP00540
APP005410
APP005420
APP005430
APP005440
APP005450
APP005460
APP005470
APP005480
APP005490
```
$A TITLE WAGENINGEN E-SEFIES PRGPELLOK CPTIMIZATION

$8 NCALC 2 NOV NSV NZVAR NMAPX IPNPUT IPDBG
$C IPRINT ITEX IGDIVR NSCAL ITRP LINQBJ NACMX
$1 ICHX FOCHM CT CTMIN CTL CTLMIN THEITA
$D2 CELFUX LCFUX ALPFX ABGXJ
$E ADVTOT 1C0J SNGNPT
$F S 0.01 1.0 0.1 SCAL 1.0
$G NDSSGN 1D0GN AMULT 1.0
$H NCONS

$11 ICRA JCON LCCA SCAL1 BU SCAL2
-1.0 +16 1.0 1.0
-1.0 +16 1.0 0.0 1.0
-1.0 +16 1.0 0.0 1.0
-1.0 +16 1.0 0.0 1.0
-1.0 +16 1.0 0.0 1.0
-1.0 +16 1.0 0.0 1.0
-1.0 +16 1.0 0.0 1.0
-1.0 +16 1.0 0.0 1.0
-1.0 +16 1.0 0.0 1.0

$V END
```
$A$ TITL
WAGENINGEN E-SERIES PROPPELLER OPTIMIZATION

$B$ NCALC
P&V
NSV
NVAR
NAPPR
INPUT
1

$C$ IPRINT
ITMAX
ICNDIR
NSCAL
ITRM
LINEBJ
NACMX
15

$D$ FOCF
FDHMIN
CT
CTMIN
CTR
CTLMIN
THETA

$E$ GCVGT
1CBJ
GCNCT

$F$ VLE
WH
X
SCAL
1
0.22
1.1
0.30
1.0
1.0
5.0
30.0
10.0
0.01
11.0
0.1
1.0
0.4
1.0
0.5
1.0
0.003
0.5
0.030
0.010

$G$ ADESSGA
IDIGN
AMLIT
1
4
23
1.0
1.0
1.0
1.0

$H$ NCON
12

$11$ ICLX
JCON
LCCX
LU
SCAL2
1
11
1.0
0.0
1.0
12
1.0
0.0
1.0
1
13
1.0
0.0
1.0
14
1.0
0.0
1.0
1
15
1.0
0.0
1.0
16
1.0
0.0
1.0
17
1.0
0.0
1.0
18
1.0
0.0
1.0
19
1.0
0.0
1.0
20
1.0
0.0
1.0
21
1.0
0.0
1.0
22
1.0
0.0
1.0

APPENDIX E

COPES OUTPUT--DESIGN CASE NO. 1
### Optimization Results

**Objective Function**

**Global Relation**

**Function Value** $0.70000000$

### Design Variables

<table>
<thead>
<tr>
<th>ID</th>
<th>D. V.</th>
<th>GL VAR NO.</th>
<th>LOW</th>
<th>VALUE</th>
<th>UPPER</th>
</tr>
</thead>
</table>

### Design Constraints

<table>
<thead>
<tr>
<th>ID</th>
<th>GL VAR NO.</th>
<th>LOW</th>
<th>VALUE</th>
<th>UPPER</th>
</tr>
</thead>
</table>

240
### Optimization Results

**Design Variables Specification:**

<table>
<thead>
<tr>
<th>Variable</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1</td>
<td>0.0024</td>
</tr>
<tr>
<td>C2</td>
<td>0.0030</td>
</tr>
</tbody>
</table>

**Environmental Parameters:**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td>20.000</td>
</tr>
</tbody>
</table>

**Fuel Parameters:**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel Efficiency</td>
<td>1.0000</td>
</tr>
<tr>
<td>Density</td>
<td>0.8000</td>
</tr>
<tr>
<td>Lower Heating Line</td>
<td>1.0000</td>
</tr>
<tr>
<td>Upper Heating Line</td>
<td>1.0000</td>
</tr>
</tbody>
</table>

**Propeller Parameters:**

<table>
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<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Blades</td>
<td>2.0000</td>
</tr>
<tr>
<td>Available Strength (PSI)</td>
<td>2500.0</td>
</tr>
</tbody>
</table>

**Objective Values:**

<table>
<thead>
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<th>Value</th>
</tr>
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<tbody>
<tr>
<td>C1</td>
<td>0.0024</td>
</tr>
<tr>
<td>C2</td>
<td>0.0030</td>
</tr>
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</table>

**Constraint Values:**

<table>
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<th>Value</th>
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<tbody>
<tr>
<td>0.0005</td>
<td>0.0005</td>
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<tr>
<td><strong>DESIGN CASE NO. 1</strong></td>
<td></td>
</tr>
<tr>
<td>-----------------------</td>
<td></td>
</tr>
<tr>
<td><strong>ENVIRONMENTAL PARAMETERS</strong></td>
<td></td>
</tr>
<tr>
<td>EXP ING F1</td>
<td>5,000.000</td>
</tr>
<tr>
<td>INLET DISTANCE (F1)</td>
<td>0.1256</td>
</tr>
<tr>
<td>OUTLET DISTANCE (F1)</td>
<td>2.173</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>NULL PARAMETERS</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>VANE FRACTION</td>
</tr>
<tr>
<td>VANE GEOMETRY EFFICIENCY</td>
</tr>
<tr>
<td>DL VANE FLOW</td>
</tr>
<tr>
<td>DL VANE STRESS</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>PROPELLER PARAMETERS</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>NUMBER OF BLADES</td>
</tr>
<tr>
<td>SELECTABLE STRESS (PSI)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>SELECTION VALUES</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>PS (PSI)</td>
</tr>
<tr>
<td>PS (PSI)</td>
</tr>
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</tr>
<tr>
<td>PS (PSI)</td>
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<tr>
<td>PS (PSI)</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>CONSTRAINT VALUES</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>MAX GRO (PSI)</td>
</tr>
<tr>
<td>HIG (PSI)</td>
</tr>
</tbody>
</table>
CCP MIP FORTRAN PROGRAM FOR
CONSTRAINED FUNCTION MINIMIZATION

INITIAL FUNCTION INFORMATICA
OBJ = -0.123456789 + 0

DECISION VARIABLES (X-VECTOR)
  1  0.300000 + 00  0.300000 + 02  0.100000 + 00  0.500000 + 00  0.300000 + 01

CONSTRAINT VALUES (C-VECTORS)
  1  -0.123456 + 01  -0.765432 + 03  -0.123456 + 05  -0.364567 + 06  -0.876543 + 07
FINAL OPTIMIZATION SUMMARY

OBJ = 6.31653e+00

JACOBIAN VARIABLES
-1.5e-08 0.9e-08 0.7e-08 0.3e-08 0.6e-08 0.4e-08 0.1e-08

CONSTRAINT VALUES (A.V. - X)
-1.5e-08 0.9e-08 0.7e-08 0.3e-08 0.6e-08 0.4e-08 0.1e-08

THERE ARE 0 ACTIVE CONSTRAINTS

THERE ARE 0 VIOLATED CONSTRAINTS

THERE ARE 0 ACTIVE SOCIETY CONSTRAINTS

NUMBER OF ITERATIONS = 70

OBJECTIVE FUNCTION WAS EVALUATED 491 TIMES

CONSTRAINT FUNCTIONS WERE EVALUATED 491 TIMES
**OPTIMIZATION RESULTS**

**GLOBAL EQUATION**

**FUNCTION VALUE** 0.0000000000

**DESIGN VARIABLES**

<table>
<thead>
<tr>
<th>ID</th>
<th>N. V.</th>
<th>GLOBAL</th>
<th>LOWER</th>
<th>SLACK</th>
<th>UPPER</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
<td>5</td>
<td>2.166e-03</td>
<td>1.167e-03</td>
<td>1.167e-03</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>4</td>
<td>5.238e-03</td>
<td>1.167e-03</td>
<td>1.167e-03</td>
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</table>

**DESIGN CONSTRAINTS**

<table>
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<tr>
<th>ID</th>
<th>GLOBAL</th>
<th>LOWER</th>
<th>VALUE</th>
<th>UPPER</th>
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</thead>
<tbody>
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<td>10</td>
<td>2</td>
<td>5</td>
<td>2.166e-03</td>
<td>1.167e-03</td>
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<td>21</td>
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<td>1.167e-03</td>
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<tr>
<td>30</td>
<td>2</td>
<td>3</td>
<td>1.167e-03</td>
<td>1.167e-03</td>
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</table>
SUBROUTINE ANALIZICALCALC

INTEGER ICALC
REAL*4 ETAO,WEIGHT,AEDVAA,DIA,N,PE,POIVV,US,TC75R,V,
RJCNL,RJCNU,R75RCL,R75RCU,AEACL,AEACCL,AEACCU,TC75CL,TC75CU,
RCMBA,DIACNL,AEACVL,TC75RS,RJ,
V,K,TC,MI,AEATRC,WATNU,TMP,NGSCRW,HCL,PATN,
PLTAV,PROMAT,DIAlM,ETARR,AEACMN,TC75MN,SC,
C75R,R75R,KT,KC,PD,VAK

COMMON /GLOEC/ETAG,WEIGHT,AEDVAA,DIA,N,PE,POIVV,US,TC75R,V,RJCNL
RJCNU,R75RCL,R75RCU,AEACL,AEACCL,AEACCU,TC75CL,TC75CU,RCMBA,DIACNU,

2AEACCL,1CSSF,SC

COMMON /FARIM/VX,TC,WT,WATRO,WATNU,TMP,NGSCRW,HCL,PATN,PWATVA,
PROMAT,DIAlM,ETARR,AEACMN,TC75MN,SC

THIS SUBROUTINE, COUPLED WITH COPES/CONMIN, CONSTITUTES ANALYSIS
METHOD FOR "DESIGN CASE 2" PROPELLER SELECTION PROBLEMS

INFLT-INITIALIZATION PHASE
PII=3.14159264
IF(.NOT.(ICLC.EQ.1))GC TO 1

SET "DESIGN CASE 2" PARAMETERS

ENVIRONMENTAL

TEMP=64.5
WATR=1.9892
WATNU=0.00011500
PATN=1.000
PWATVA=2.95435291

PROPELLER PARAMETERS

Z=6.6
PRMAT=5.0

HULL PARAMETERS

M1=0.22
TC=0.15
ETARR=1.425
NGSCK=1.0
HCL=21.9871

DIAM=30.0

SET DESIGN VARIABLES FIELD FIXED FOR "DESIGN CASE 2"

APPCC0010
APPCC0030
APPCC0040
APPCC0080
APPCC0100
APPCC0110
APPCC0120
APPCC0130
APPCC0140
APPCC0150
APPCC0160
APPCC0170
APPCC0180
APPCC0190
APPCC0200
APPCC0210
APPCC0220
APPCC0230
APPCC0240
APPCC0250
APPCC0260
APPCC0270
APPCC0280
APPCC0290
APPCC0300
APPCC0310
APPCC0320
APPCC0330
APPCC0340
APPCC0350
APPCC0360
APPCC0370
APPCC0380
APPCC0390
APPCC0400
APPCC0410
APPCC0420
APPCC0430
APPCC0440
APPCC0450
APPCC0460
APPCC0470
APPCC0480
GO TO 3

EXECUTION PHASE

1 CONTINUE
   IF (NOT ((ICALC.EC.2=1)) GC TO 2
   TC75R=((0.0635*0.0025*2)+1/(2.073*AECVAG))
   CALL RICAL(DIA)
   CALL CR75R(C75R,R75R)
   CALL CEFP5(RJ,R75R,KT,JK)
   CALL OFPEFF(RJ,KT,JK,ETAQ)
   CALL ACPEF(KT,PE)
   CALL JCAF(RJ,RJ,RCJ,RC)
   CALL RECN4A(R75R,R75R,CT75R)
   CALL EICCA(AECVAG,TC75R,AECVAG,TC75R,TC75CL,TC75CL)
   CALL BPOM2(KL,PL,BAL)
   CALL DIGNUA(DICNUA)
   CALL CEVN4A(KT,AECVAG)
   CALL STICNUA(KT,CT75R,TC75R)

2 CONTINUE

GO TO 3

OUTPUT-RESULT PHASE

VK=V/1.088
VAK=(V-6.0)/VK
PC=(2,101/256)/33000.0
WRITE(6,90001)
WRITE(6,90010)
WRITE(6,90021)
WRITE(6,90031)
WRITE(6,90041)
WRITE(6,90051)
IFL. NO1.(PRMAT.EC.1.0) GC TO 81
WRITE(6,90051SC)
GC TO 66
CONTINUE

IFL. NO1.(PRMAT.EC.2.0) GC TO 82

GO TO 3
WRITE(6,5006) SC
82
GE TC 66
CENTINLE
IF (NCL, (PRFMT, LG, 83.0116C TO 83
WRITE(6,5001)SC
83
GE TC 66
CENTINLE
IF (NCL, (PRFMT, LG, 8.0116C TO 84
WRITE(6,5008)SC
84
GE TC 66
CENTINLE
IF (NCL, (PRFMT, LG, 8.0116C TO 85
WRITE(6,5001)SC
85
GE TC 66
CENTINLE
WRITE(6,9010)
86
CENTINLE
WRITE(6,9011)PSE, V, VK, WAK, NLS, P, R, KT, KQ, ETAQ, K75R, DIA,
WRITE(6,9012)CIALIN, AEAOMN, IC75MN
3 CONTINUE
RETURN
C C MISCELLANEOUS FORMAT STATEMENTS
C 9000 FORMAT(* , *) , OPTIMIZATION RESULTS ------- DESIGN CASE NO., /,
1 * , SUEROUTINE "STRGMA", //
9001 FORMAT(1X, 'DESIGN VARIABLES SPECIFIED: QS, AV, TC75R, //
9002 FORMAT(1X, 'ENVIRONMENTAL PARAMETERS: TEMP (deg F), 22X, //
1/ 31X, 'Economy (lbf/sec/ft^4), 12X, F10.4, //
1/ 31X, 'VISCOSITY (ft^2/sec), 15X, F10.4, //
1/ 31X, 'ATMOSPHERIC PRESSURE (PSIA), 7X, F10.4, //
1/ 31X, 'WATER VAPORIZATION PRESSURE (PSIA), 5X, F10.4, //
9003 FORMAT(1X, 'FULL PARAMETERS: 1X, 'X, 'F10.4, //
1/ 31X, 'Y, 'F10.4, //
1/ 31X, 'Z, 'F10.4, //
1/ 31X, 'RELATIVE ROTATION EFFICIENCY, 1X, E10.4, //
1/ 31X, 'NUMBER OF PROPELLERS, 14X, F10.1, //
1/ 31X, 'DEPTH IC SHAFT CENTERLINE (FT), 4X, F10.4, //
1/ 31X, 'DIAMETER LIMIT (FT), 15X, F10.4, //
9004 FORMAT(1X, 'PROPELLER PARAMETERS: 1X, 'X, 'F10.4, //
1/ 31X, 'Y, 'F10.4, //
1/ 31X, 'Z, 'F10.4, //
9005 FORMAT(1X, 'MATERIAL TYPE, 21X, 'CAST IRON', //
1/ 31X, 'ALLIGABLE STRESS (PSI), 12X, F10.1, //
9006 FORMAT(1X, 'MATERIAL TYPE, 21X, 'CAST STEEL', //
1/ 31X, 'ALLIGABLE STRESS (PSI), 12X, F10.1, //
9007 FORMAT(1X, 'MATERIAL TYPE, 21X, 'BRONZE', //
1/ 31X, 'ALLIGABLE STRESS (PSI), 12X, F10.1, //
APPCCS70
APPCCS60
APPCC590
APP00400
APP01010
APP01020
APP01030
APP01040
APP01050
APP01060
APP01070
APP01080
APP01090
APP01100
APP01110
APP01120
APP01130
APP01140
APP01150
APP01160
APP01170
APP01180
APP01190
APP01200
APP01210
APP01220
APP01230
APP01240
APP01250
APP01260
APP01270
APP01280
APP01290
APP01300
APP01310
APP01320
APP01330
APP01340
APP01350
APP01360
APP01370
APP01380
APP01390
APP01400
APP01410
APP01420
APP01430
APP01440
<table>
<thead>
<tr>
<th>FORMAT</th>
<th>DESCRIPTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>9006</td>
<td>MATERIAL TYPE, ALL ALLOWABLE STRESS (PSI), SELECTED VALUES (1F10.4), END</td>
</tr>
<tr>
<td>9007</td>
<td>MATERIAL TYPE, ALL ALLOWABLE STRESS (PSI), SELECTED VALUES (1F10.4), END</td>
</tr>
<tr>
<td>9008</td>
<td>MATERIAL TYPE, ALL ALLOWABLE STRESS (PSI), SELECTED VALUES (1F10.4), END</td>
</tr>
<tr>
<td>9009</td>
<td>MATERIAL TYPE, ALL ALLOWABLE STRESS (PSI), SELECTED VALUES (1F10.4), END</td>
</tr>
<tr>
<td>9010</td>
<td>MATERIAL TYPE, ALL ALLOWABLE STRESS (PSI), SELECTED VALUES (1F10.4), END</td>
</tr>
<tr>
<td>9011</td>
<td>MATERIAL TYPE, ALL ALLOWABLE STRESS (PSI), SELECTED VALUES (1F10.4), END</td>
</tr>
<tr>
<td>9012</td>
<td>MATERIAL TYPE, ALL ALLOWABLE STRESS (PSI), SELECTED VALUES (1F10.4), END</td>
</tr>
</tbody>
</table>

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SUBROUTINE ANALIZ(ICALC)
INTEGER*4 ICALC
REAL*4 ETAQ, HEIGHT, AEDVAD, DIA, N, PE, PDIVC, QS, TL75K, Vr
1 RJCNL, R75KL, R75RCU, AEAACL, AEACL, TC75CL, TC75CU,
2 FCWAL, DIACNU, AEADCV, TCSTAS, RJ,
3 VK, TC, WT, Z, WATK, WATNU, TEMP, NGSCRM, HCL, PATH,
4 FMTA, PRMAT, DIAM, ETARK, AEADPR, TC75MN, SC,
5 C15R, R15R, K, KG, PDO, VAK
COMMON /CLGECM/ETAC, HEIGHT, AEDVAD, DIA, N, PE, PDIVC, QS, TL75K, Vr, RJCNL,
1 RJCNL, R75KL, R75RCU, AEAACL, AEACL, TC75CL, TC75CU,
2 AEADCV, TCSTAS, RJ
COMMON /PARAM/ VK, TC, WT, Z, WATK, WATNU, TEMP, NGSCRM, HCL, PATH, PWAIVA,
1 PROMAT, IAIAH, ETARK, AEADAN, TC75MN, SC

THIS SUBROUTINE COUPLED WITH COPES/CMAP, CONSTITUTES ANALYSIS
METHOD FOR "DESIGN CASE 2" PROPELLER SELECTION PROBLEMS

INPLT-INITIALIZATION PHASE

PII = 3.14159265
IF(1 .NOT. IICALC .EQ. 1) GO TO 1

SET "DESIGN CASE 2" PARAMETERS
ENVIROMENTAL
TEMP=64.4
WATK=1.9852
WATNU=0.00011500
PATH=14.691
PWAIVA=295439651
PECFELLER PARAMETERS
Z=6.0
PRMAT=5.0
HULL PARAMETERS
WT=2.5
ETC=1.5
ETARK=1.025
NGSCRM=1.0
HCL=21.9827
DIAM=30.0

SET DESIGN VARIABLES FELD FIXED FOR "DESIGN CASE 2"
CC ENC OF INPUT-INITIALIZATION PHASE
CC GO TO 3
CC EXECUTION PHASE

1 CONTINUE
IF (.NOT. (ICALC.EQ.21)) GO TO 2
TC75R= (10.0185-0.0123*Z1+Z1/12.073*AEVAD/ 
CALL RICALL(DIA) 
CALL C75RA(1,75R1) 
CALL RX75R(1,75R1) 
CALL CCEFSAIRU75R1,75C3,75R1,75TQ) 
CALL QREFF(RJ,75R1,75C3,75TQ,ETAQ) 
CALL CALCPK(75R1,75P) 
CALL JCNAI(RJ,75R1,75C3,75TQ) 
CALL RYVCNA(75R1,75R1,75C3,75R1,75C3) 
CALL EXICCNZ(75R1,75C3,75R1,75C3,75C3,75C3,75C3,75C3,75C3) 
CALL BIPON2(K1,POWAPP1) 
CALL DICOJQ(75R1,75C3) 
CALL CAVCNK(75R1,75C3,75C3,75C3,75C3) 
CALL STCNK(K1,75R1,75C3,75C3,75C3) 

CC ENC OF EXECUTION PHASE
CC GO TO 3

2 CONTINUE

CC OUTPUT-RESULT PHASE

VK=V/1.688 
VAK=1.0-WT1*VK 
PE=12.0*PI*95*N1/33000.0 
WRITE(6,500) 
WRITE(6,9000) 
WRITE(6,9002) TEMP, WATRO, WATN, FATT, PWATVA 
WRITE(6,9003) W1, W1, ETARR, NOSC, HCL, DIALIN 
WRITE(6,9004) 
IF (.NOT. (PREMAT.EQ.1.0)) GC TO 81 
WRITE(6,9005) 
GC TO 86 
CONTINUE 
IF (.NOT. (PREMAT.EQ.2.0)) GC TO 82
WRITE(6,506)SC
GC IC 6
CONTINUE
IF (.NOT. PROMAT.EQ.3) GC 10 63
WRITE(6,507)SC
GC IC 6
CONTINUE
IF (.NOT. PROMAT.EQ.4) GC 10 64
WRITE(6,508)SC
GC IC 6
CONTINUE
IF (.NOT. PROMAT.EQ.5) GC 10 65
WRITE(6,509)

1 WRITE(6,9011)PE, V, VK, VAK, NQS, PD, RJ, KT, KQ, ETAQ, R75R, DIA,
1 PCIVL, ALVDAO, TC75R
3 CONTINUE
RETURN

C MISCELLANEOUS FORMAT STATEMENTS
9000 FORMAT(*'*** OPTIMIZATION RESULTS ---------- DESIGN CASE NUM: 2*'*','')
9001 FORMAT(*'*** DESIGN VARIABLES SPECIFIED: GS:*V:IC75R:*')
9002 FORMAT(*'*** ENVIRONMENTAL PARAMETERS: TEMP (DEG F): 22X:*','')
9003 FORMAT(*'*** FULL PARAMETERS: 13X:*WIRE FRACTION: 21X:*','')
9004 FORMAT(*'*** PROPELLER PARAMETERS: 8X:*NUMBER OF BLADES: 18X:*','')
9005 FORMAT(*'*** MATERIAL TYPE: 21X:*','')
9006 FORMAT(*'*** ALLWABLE STRESS (PSI): 12X:*','')
9007 FORMAT(*'*** ALLWABLE STRESS (PSI): 12X:*','')

C
SUBROUTINE ANALIZE(ICALC)
INTEGER*4 *CALC
REAL*4 ETAQ,WEIGHT,AEDVAC,DIA,N,PE,FDIV,GS,TC75R,V,
1 RICAL,RJCNV,R75RCU,AEACL,AEACU,TC75CL,TC75CU,
2 FOBAL,DIALM,AEDLV,TCSTNB,RJ,
3 VT,TC,WZ,ATR,WAINU,TEMP,AGSCEW,HCL,PATH,
4 PHAT,IPROMAT,DIALIM,ETARR,AEADN,TC75MN,SC,
5 C75R,R75R,KT,KC,PD,VAK
COMMON /IGLDECM/ETAQ,_WEIGHT,AEDVAC,DIA,N,PE,FDIV,GS,TC75R,V,RJCNV,
1 RICAL,R75RCU,AEACL,AEACU,TC75CL,TC75CU,FOBAL,DIALM,AEDLV
2 AEACL,TCSTNB,RJ
COMMON /IPARAM/VK,TC,WZ,ATR,WAINU,TEPP,AGSCEW,HCL,PATH,PHAT,IPROMAT,
1 PRIMAT,DIALM,ETARR,AEADN,TC75MN,SC

THIS SUBROUTINE, COUPLED WITH CGPES/COMPIN, CONSTITUTES ANALYSIS
METHOD FOR "DESIGN CASE 2" PROPELLER SELECTION PROBLEMS

INPUT-INITIALIZATION PHASE

II=3.14159265
IF (NOT.(ICALC.EQ.1))GO TO 1

SET "DESIGN CASE 2" PARAMETERS

ENVIRONMENTAL

TEMP=64.4
WATRO=1.9852
WATIN=4000.015900
PATH=14.637
PHATVX=2.94535291

PROPELLER PARAMETERS

Z=6.0
PRCNT=5.0

HULL PARAMETERS

WT=0.22
TC=0.28
ETARR=1.025
AGSCEW=1.0
HCL=21.5827
DIALIN=30.0

SET DESIGN VARIABLES HELD FIXED FOR "DESIGN CASE 2"
QS=1211125.635
N=110.

END OF INPUT-INITIALIZATION PHASE

GO TO 3

EXECUTION PHASE

1 CONTINUE
IF(LICALL,EC .2) GC TO 2
CALL RICALQ1A
CALL RCFAI(C75R)
CALL REY75RI(C75R,R75R)
CALL CCEFSAI(RJ,R75R,KT,KQ)
CALL DNFERRJ(RJ,KT,KQ)
CALL LACPLKJ
CALL JCNARJ(RJ,RJCNL,RJCNL)
CALL REYCNARJ(R75R,R75RCNY,R75CNU)
CALL EXTNKJ,AE0VAO1,TC75K,AEACL,AEACU,TC75CL,TC75CU
CALL BLPON2IK,IPON2IK
CALL DIGNUA(DIACAL)
CALL CAVNCRAK1,AEACCV1
CALL STRNCRAK1(C75R,TCSTRS)

END OF EXECUTION PHASE

GO TO 3

2 CONTINUE

OUTPUT-RESULT PHASE

VK=V/1.688
VAK=V/1.688
PL=1.0*PL/1/QS*N/33000.0
WRITE(6,9000)
WRITE(6,994)
WRITE(6,9902) TEMP,WATRO,WAINU,PAIV,PAIVA
WRITE(6,9903) W1,T,ETARR,NOSCR,HCL,DIAVIM
WRITE(6,9904) Z
IF(LICALL,EC .2) GC TO 81
WRITE(6,9905) SC
GC TO 68

81 CENTINUE
IF(LICALL,EC .2) GC TO 82
WRITE(6,9906) SC
GC TO 68

82 CENTINUE
IF: NOT (PRCMAT.EQ.3) GOTO 83
WRITE(6,9007)

83 CCONTINUE
IF: NOT (PRCMAT.EQ.4) GOTO 84
WRITE(6,9008)

84 CCONTINUE
IF: NOT (PRCMAT.EQ.5) GOTO 85
WRITE(6,9010)

85 CCONTINUE
WRITE(6,9011)

1 CONTINUE
WRITE(6,9012)

3 CONTINUE
RETURN

CC
MISCELLANEOUS FORMAT STATEMENTS

9000 FORMAT('1x', 'OPTIMIZATION RESULTS ------ DESIGN CASE NO.: 2',/ 
1 'x', 'SUBROUTINE "STRCNA" ; )',/ 
9001 FORMAT('1x', 'DESIGN VARIABLES SPECIFIED: G5x',/ 
9002 FORMAT('1x', 'ENVIRONMENTAL PARAMETERS: TEMPERATURE F1x, 22x',/ 
1 'F1x', 'DENSITY (LBF-SEC2/FT4)', '12x', 'F10.4',/ 
2 '1x', 'VISCOITY (FT2/SEC)', '15x', 'F10.4',/ 
3 '1x', 'ATMOSPHERIC PRESSURE (PSIA)', '7x', 'F10.4',/ 
4 '1x', 'WATER VAPORIZATION PRESSURE (PSIA)', 'F10.4',/ 
9003 FORMAT('1x', 'FULL PARAMETERS: 12x', '15x', 'F10.4',/ 
1 '1x', 'THRUST DEDUCTION FRACTION', '9x', 'F10.4',/ 
2 '1x', 'RELATIVE ROTATIVE EFFICIENCY', '6x', 'F10.4',/ 
3 '1x', 'NUMBER OF PROPELLERS', '12x', 'F10.4',/ 
4 '1x', 'DEPTH TO SHAFT CENTERLINE (FT)', '4x', 'F10.4',/ 
5 '1x', 'DIAMETER LIMIT (FT)', '15x', 'F10.4',/ 
9004 FORMAT('1x', 'PROPELLER PARAMETERS: 8x', 'ALMNBF OF BLADES', '18x',/ 
1 '1x', 'MATERIAL TYPE', '21x', 'CAST IRON',/ 
2 '1x', 'ALLCABLE STRESS (PSI)', '12x', 'F10.1',/ 
9006 FORMAT('1x', 'MATERIAL TYPE', '21x', 'CAST STEEL',/ 
1 '1x', 'ALLCABLE STRESS (PSI)', '12x', 'F10.1',/ 
9007 FORMAT('1x', 'MATERIAL TYPE', '21x', 'BRONZE',/ 
1 '1x', 'ALLCABLE STRESS (PSI)', '12x', 'F10.1',/ 
9008 FORMAT('1x', 'MATERIAL TYPE', '21x', 'AL-2L BRONZE',/ 
1 '1x', 'ALLCABLE STRESS (PSI)', '12x', 'F10.1',/ 
9009 FORMAT('1x', 'MATERIAL TYPE', '21x', 'STAINLESS STEEL',/ 
1 '1x', 'ALLCABLE STRESS (PSI)', '12x', 'F10.1',/
**9010 FORMAT**

1X,25X, 'ALLCHABLE_STRESS (PSI) ', 12X, = , 'F10.4', /

**9011 FORMAT**

1X,25X, 'MATERIAL_TYPE ', 21X, = , 'NCT CONSIDERED', /

**9012 FORMAT**


1X,25X, 'V (FT/SEC)', 23X, = , 'F10.4' /

1X,25X, 'VA (KNOTS)', 23X, = , 'F10.4' /

1X,25X, 'K (RPM)', 23X, = , 'F10.4' /

1X,25X, 'PD (FT-LBF)', 23X, = , 'F10.4' /

1X,25X, 'PO (HP)', 23X, = , 'F10.4' /

1X,25X, 'J', 23X, = , 'F10.4' /

1X,25X, 'JT', 23X, = , 'F10.4' /

1X,25X, 'KQ', 23X, = , 'F10.4' /

1X,25X, 'REVT5R', 23X, = , 'F10.4' /

1X,25X, 'JIA (FT)', 23X, = , 'F10.4' /

1X,25X, 'PO', 23X, = , 'F10.4' /

1X,25X, 'AE/AQ', 23X, = , 'F10.4' /

1X,25X, 'T/C .75R', 23X, = , 'F10.4' /

**9013 FORMAT**

1X,25X, 'CONSTRAINT VALUES', 11X, 'MAX DIA (FT) ', 22X, = , 'F10.4' /

1X,25X, 'MIN ACE/AQ', 25X, = , 'F10.4' /

1X,25X, 'MIN T/C .75R', 22X, = , 'F10.8'
SUBROUTINE ANALYZICALC
INTEGER ICALC
REAL ETAO,WEIGHT,AEOLV,CSA,N,PE,PDIVQ,IC75R,VL
RJCNL,RJGNU,R75RCU,AEACL,AEACC,TC75CL,TC75CU,
FCWBL,DIACNU,AEOLCV,TCSTI,RI,
VR,IC,W,T,WT,WARC,WAINU,TEMP,AGSRW,ACL,PAIM,
PMATA,PMAT,M,DIAM,ETARK,AR,MCN,TC75MN,SC;
COMMON /GLOCN,ETAOM,WEIGHT,AEOLV,CSA,N,PE,PDIVQ,IC75R,VL,RJCNL,
RJGNU,R75RCU,AEACL,AEACC,TC75CL,TC75CU,POWDAI,DIACNU,
2,AEOLCV,TCSTI,RI,
COMMON /PARAMT,W,T,WT,WARC,WAINU,TEMP,AGSRW,ACL,PAIM,PMATA,
IPRCMAT,DIAM,ETARK,AR,MCN,TC75MN,SC;
THIS SUBROUTINE, COUPLED WITH COPES/COFIN, CONSTITUTES ANALYSIS
METHOD FOR "DESIGN CASE 2" PROPULSOME SELECTION PROBLEMS
INPUT-INITIALIZATION PHASE
PI1=3.14159265
IF(1, NOT.(ICALC.EQ.1)) GO TO 1

SET "DESIGN CASE 2" PARAMETERS
ENVIRONMENTAL
TEMP=314.4
WAINU=0.00011900
PAIM=14.697
PMATA=295435291

PROPULSOME PARAMETERS
Z=6.0
PRMAT=5.0

HULL PARAMETERS
HT=C,24
TC=C,15
ETAR=1.025
NCSCR=31.0
ML=1=1.982
DIALIM=30.0

SET DESIGN VARIABLES HELD FIXED FOR "DESIGN CASE 2"
APP05110
APP05120
APP05130
APP05140
APP05150
APP05160
APP05170
APP05180
APP05190
APP05200
APP05210
APP05220
APP05230
APP05240
APP05250
APP05260
APP05270
APP05280
APP05290
APP05300
APP05310
APP05320
APP05330
APP05340
APP05350
APP05360
APP05370
APP05380
APP05390
APP05400
APP05410
APP05420
APP05430
APP05440
APP05450
APP05460
APP05470
APP05480
APP05490
APP05500
APP05510
APP05520
APP05530
APP05540
APP05550
APP05560
APP05570
APP05580
QS=121\times 125.835  
N=110.2

ENC OF INPUT-INITIALIZE PHASE

GO TO 3

EXECUTION PHASE

1 CONTINUE

IF (NOT (.1CALC.EQ.2)) GC TO 2

CALL RGCAL(DIA)
CALL C75RA(C75R)
CALL RE75R(C75R, R75R)
CALL CLEFSA(R, R75R, KT, KO)
CALL GWEFE(R, KT, KQ, ETA1)
CALL GALTPE(KT, PE1)
CALL JCNC(A, R, RNC, RNCU)
CALL REVCN(R75R, C75R, R75RCU)
CALL EXTN(C1, AEAVG, TC75R, AEACL, AEACU, TC75CL, TC75CU)
CALL BIPMS2(KC, PDBAL)
CALL DICN(A, DIA, DIA1)
CALL CAVCNA1(KC, AEACV)
CALL STRCN(KC, KT, C75R, TCSTR)

ENC OF EXECUTION PHASE

GO TO 3

2 CONTINUE

OUTPUT-RESULT PHASE

VK=\sqrt[1.688]{V}
VK=(1.0-WT)*VK
PC=(2.0*CPI/[\text{QS}+N/33000.0]
WRITE(6,3001)
WRITE(6,9002) TEMP_1, MATU, WATU, FATM, PMAI, VTA
WRITE(6,9003) WT, TD, ETARR, NSRCL, HCL, DIALIM
WRITE(6,9004) Z
IF (NOT (.1PRGMAT.EQ.1.0)) GC TO 81
WRITE(6,9005) SC

81 CONTINUE

IF (.NOT (.1PRGMAT.EQ.2.0)) GC TO 82
WRITE(6,9006) SC

82 CONTINUE
IF .NOT.(PRMAT.EQ.3.0))GO TO 83
WRITE(*,9007)SC
83 CONTINUE
IF .NOT.(PRMAT.EQ.4.0))GO TO 84
WRITE(*,9008)SC
84 CONTINUE
IF .NOT.(PRMAT.EQ.5.0))GO TO 85
WRITE(*,9009)SC
85 CONTINUE
WRITE(*,9010)
86 CONTINUE
WRITE(*,9011)PE,Wm,VAK,NS,**,RJ,KT,KG,ETA0,R75K,DIA,
1 PEIV,ACVAG,ICT75,
3 CONTINUE
RETURN
C MISCELLANEOUS FORMAT STATEMENTS
C
9000 FORMAT(*'OPTIMIZATION RESULTS ------ DESIGN CASE NO. 2*/*',//)
9001 FORMAT(*'DESIGN VARIABLES SPECIFIED: **',//)
9002 FORMAT(*'ENVIRONMENTAL PARAMETERS: *TEMP (DEG F), 2X,*' ),//)
  1 F10.4,/*
  4 1X,25X,**G~N~SITY (LBE-SEC/FT4), 12X,**,F10.4,/*
  3 1X,25X,**VISCOSITY (FT2/SEC), 15X,**,E16.9,/*
  3 1X,25X,**ATMOSPHERIC PRESSURE (PSIA), 1X,**,F10.4,/*
  4 1X,25X,**WATER VAPORIZATION PRESSURE (PSIA), 1X,**,F10.4,/*
9003 FORMAT(*'FULL PARAMETERS: 13X,**MADE FRACTION**, 2X,**,F10.4,/*
  4 1X,25X,**THRUST DED UCTION FRACTION**, 9X,**,F10.4,/*
  3 1X,25X,**RELATIVE ROTATIVE EFFICIENCY**, 6X,**,F10.4,/*
  3 1X,25X,**NUMBER OF PROPELLERS**, 14X,**,F10.4,/*
  4 1X,25X,**DEPTH TO SHAFT CENTERLINE (FT)**, 4X,**,F10.4,/*
  2 1X,25X,**DIAMETER LIMIT (FT)**, 15X,**,F10.4,/*
9004 FORMAT(*'PROPELLER PARAMETERS: 8X,**NUMBER OF BLADES**, 18X,**',//)
  1 F10.4,/*
9005 FORMAT(*'MATERIAL TYPE**, 21X,**,CAST IRON**),//)
  1 1X,25X,**ALLOWABLE STRESS (PSI)**, 12X,**,F10.4,/*
9006 FORMAT(*'MATERIAL TYPE**, 21X,**,CAST STEEL**),//)
  1 1X,25X,**ALLOWABLE STRESS (PSI)**, 12X,**,F10.4,/*
9007 FORMAT(*'MATERIAL TYPE**, 21X,**,BRONZE**),//)
  1 1X,25X,**ALLOWABLE STRESS (PSI)**, 12X,**,F10.4,/*
9008 FORMAT(*'MATERIAL TYPE**, 21X,**,K-AL BRONZE**),//)
  1 1X,25X,**ALLOWABLE STRESS (PSI)**, 12X,**,F10.4,/*
9009 FORMAT(*'MATERIAL TYPE**, 21X,**,STAINLESS STEEL**),//)
  1 1X,25X,**ALLOWABLE STRESS (PSI)**, 12X,**,F10.4,/*
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<thead>
<tr>
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<tr>
<td>9010</td>
<td><em>ALLOWABLE STRESS (PSI)</em></td>
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<td></td>
<td><em>ELECTION VALUES</em></td>
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<tr>
<td>9012</td>
<td><em>CONSTRAINT VALUES</em></td>
</tr>
</tbody>
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```
1 | 1X,25X, 'ALLOWABLE STRESS (PSI)' , 1X, ' ' , F10.4 / , APP06550
2 | 1X,25X, 'MATERIAL TYPE' , 1X, ' ' , F10.4 / , APP06550
3 | 1X,25X, 'ELECTION VALUES' , 12X, ' ' , F10.4 / , APP06550
4 | 1X,25X, 'CS (FT-LBF)' , 23X, ' ' , F10.4 / , APP06550
5 | 1X,25X, 'PD (HP)' , 23X, ' ' , F10.4 / , APP06550
6 | 1X,25X, 'J' , 23X, ' ' , F10.4 / , APP06550
7 | 1X,25X, 'IEAC' , 23X, ' ' , F10.4 / , APP06550
8 | 1X,25X, 'EY75R' , 23X, ' ' , F10.4 / , APP06550
9 | 1X,25X, 'IA (FT)' , 23X, ' ' , F10.4 / , APP06550
10 | 1X,25X, 'P/D' , 23X, ' ' , F10.4 / , APP06550
11 | 1X,25X, 'AE/AG' , 23X, ' ' , F10.4 / , APP06550
12 | 1X,25X, 'T/C .75R' , 23X, ' ' , F10.4 / , APP06550
13 | 1X,25X, 'P/N 1/C .75R' , 23X, ' ' , F10.4 / , APP06550
END
```
PRELIMINARY PROPELLER SELECTION USING THE WAGENINGEN B-SCREW SERIES AND A GENERAL PURPOSE NON-LINEAR OPTIMIZER (U) NAVAL POSTGRADUATE SCHOOL MONTEREY CA
M P SMITH JUN 83
<table>
<thead>
<tr>
<th>TITLE</th>
<th>WAGENINGEN B-SERIES PROPELLER OPTIMIZATION</th>
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</thead>
<tbody>
<tr>
<td>$b$</td>
<td>NCALC 3, ADV 0, NSV 0, NZVAR 0, NAPRX 0, IINPUT 0, IPDBG 0</td>
</tr>
<tr>
<td>$c$</td>
<td>IPRINT 1, ITMAX 1000, ICNDIK 0, NSCAL -1, ITRM 3C, LINOBJ 15, NACMAX 15</td>
</tr>
<tr>
<td>$d$</td>
<td>FOCM 0.001, FOCH 0.001, CT CTMIN, CTRT CTLMIN, THETA</td>
</tr>
<tr>
<td>$d_e$</td>
<td>DEFUN 0, CDFUN 0, ALPHAX ABUBJ1</td>
</tr>
<tr>
<td>$e$</td>
<td>ADVTOT 0.10, ICBJ SGNPT</td>
</tr>
<tr>
<td>$f$</td>
<td>VNE 0.4, VNB 1.0, SCA 0.40, X 1.00</td>
</tr>
<tr>
<td>$g$</td>
<td>NDSTG 0.9, IDIGN 1.0, AMULT 1.0</td>
</tr>
<tr>
<td>$h$</td>
<td>NCUNS 0.10, TCON 1.0, JCON JCON, LCON LCON</td>
</tr>
<tr>
<td>$h_i$</td>
<td>11 ICBJ 11, 12 ICBJ 12, 13 ICBJ 13, 14 ICBJ 14, 15 ICBJ 15, 16 ICBJ 16, 17 ICBJ 17, 18 ICBJ 18, 19 ICBJ 19, 20 ICBJ 20, 21 ICBJ 21</td>
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<tr>
<td>$h_j$</td>
<td>SCAL 11, 12 SCAL 12, 13 SCAL 13, 14 SCAL 14, 15 SCAL 15, 16 SCAL 16, 17 SCAL 17, 18 SCAL 18, 19 SCAL 19, 20 SCAL 20, 21 SCAL 21</td>
</tr>
<tr>
<td>$h_k$</td>
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<tr>
<td>END</td>
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APPENDIX H

COPES OUTPUT--DESIGN CASE NO. 2
<table>
<thead>
<tr>
<th>OPTIMIZATION RESULTS</th>
<th>DESIGN CASE NO. 2</th>
<th>SUBROUTINE &quot;STARA&quot;</th>
</tr>
</thead>
<tbody>
<tr>
<td>DESIGN VARIABLES SPECIFIED</td>
<td>U.S.A.V.10270</td>
<td></td>
</tr>
<tr>
<td>ENVIRONMENTAL PARAMETERS:</td>
<td></td>
<td>0.13000</td>
</tr>
<tr>
<td></td>
<td>0.27000</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.50000</td>
<td></td>
</tr>
<tr>
<td>M-fluid PARAMETERS:</td>
<td></td>
<td>0.13000</td>
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<tr>
<td></td>
<td>0.27000</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.50000</td>
<td></td>
</tr>
<tr>
<td>PROPELLER PARAMETERS:</td>
<td></td>
<td>0.13000</td>
</tr>
<tr>
<td></td>
<td>0.27000</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.50000</td>
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</tr>
<tr>
<td>SELECTION VALUES:</td>
<td></td>
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</tr>
<tr>
<td></td>
<td>0.27000</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.50000</td>
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</tr>
<tr>
<td>CONSTRAINT VALUES:</td>
<td></td>
<td>0.13000</td>
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<tr>
<td></td>
<td>0.27000</td>
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</tr>
<tr>
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</tbody>
</table>
**FINDINGS**

**CONTROL VARIABLES**

<table>
<thead>
<tr>
<th>Name</th>
<th>Value</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
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</tbody>
</table>

**CALCULATION CONTROL, ANALYSIS**

<table>
<thead>
<tr>
<th>Name</th>
<th>Value</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*** * * EQUATION INFORMATION**

- **MODEL ERROR**: 0.1000E+01
- **COMPARISONS**: 1 if zero, compare default Bell Group

**SPRING DATA**

<table>
<thead>
<tr>
<th>Name</th>
<th>Value</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
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**DESIGN KEYS**

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<tr>
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**DESIGN VARIABLES**

<table>
<thead>
<tr>
<th>Name</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
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</tbody>
</table>

**CONSTRAINT INFORMATION**

<table>
<thead>
<tr>
<th>Name</th>
<th>Value</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
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**TOTAL NUMBER OF CONSTRAINTS**

<table>
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<tr>
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</thead>
<tbody>
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</table>

<p>| 10    | 001   |                |
| 10    | 002   |                |
| 10    | 003   |                |</p>
<table>
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<tr>
<th>OPTIMIZED RESULTS</th>
<th>ULES EA [lbs]</th>
<th>M.</th>
<th>SUBCUTINE [PSIG]</th>
</tr>
</thead>
<tbody>
<tr>
<td>DESIGN VARIABLES SPECIES</td>
<td>W.P.B.G, N.D.T</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ENVIRONMENTAL PARAMETERS</td>
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<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
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<tr>
<td>FULL PARAMETERS</td>
<td></td>
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<td></td>
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<td></td>
</tr>
<tr>
<td>PROPELLER PARAMETERS</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SELECTION VALUES</td>
<td></td>
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</tr>
<tr>
<td>CONSTRAINT VALUES</td>
<td></td>
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</tr>
</tbody>
</table>
INITIAL FUNCTION INFORMATION
OBJ: -C.3142052+4C
DEF. 9 1.000000E+00 0.10000E+01
CONSTRAINT VALUES (GECHEM):
91 -2.54461E-01 -2.41738E-01 -4.00416E+05 -8.23816E+05 0.10000E+00 0.40000E+00
### Final Optimization Information

| Objective Function Value | Decision Variables
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<tbody>
<tr>
<td>-6.659922E+00</td>
<td>0.653979E+00</td>
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</table>

**Constraint Values (x-vector):

<table>
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<tr>
<th>Constraint</th>
<th>Value 1</th>
<th>Value 2</th>
<th>Value 3</th>
<th>Value 4</th>
</tr>
</thead>
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<td></td>
<td>-2.12320E-01</td>
<td>-8.91421E-07</td>
<td>-2.23060E-05</td>
<td>3.72164E+00</td>
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</table>

**Summary:

- **Number of Constraints:** 0
- **Number of Violated Constraints:** 0
- **Number of Active Side Constraints:** 0
- **Termination Criterion:** GAMS/COPT/Objec/11145 less than GAMS/PR/30 iterations
- **Number of Iterations:** 25
- **Objective Function Evaluated:** 230 Times
- **Constraint Functions Evaluated:** 230 Times
OPTIMIZATION RESULTS

LOCAL EQUATION: 1  FUNCTION VALUE 0.64999E+100

DESIGN VARIABLES

<table>
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<th>LOCAL</th>
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DESIGN CONSTRAINTS

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<tr>
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<tr>
<td>OPTIMIZATION RESULTS ----</td>
<td>DESIGN CASE NO. 2</td>
<td>SUBPROBLEM &quot;STACK&quot;</td>
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<tr>
<td>---------------------------</td>
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<tr>
<td>DESIGN VARIABLES SPECIFIC</td>
<td>W3.9, x = 46.75A</td>
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<td>PROPELLER PARAMETERS:</td>
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<td>SELECTION VALUES:</td>
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<td>CONSTRAINT VALUES:</td>
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### DESIGN VARIABLES

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<th>Note</th>
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### CONSTRAINT INFORMATION

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<th>Constraint</th>
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### RESULTS

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<th>Objective</th>
<th>Constraints</th>
<th>Values</th>
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</thead>
</table>

**Explanation:**

- The document appears to be a technical report or a section from a machine learning or computational model optimization project, possibly related to a specific statistical analysis or algorithm setup.

- The content includes tables and possibly data points, with headers indicating parameters or variables related to a design process or optimization problem.
<table>
<thead>
<tr>
<th>OPTIMIZATION RESULTS</th>
<th>USER CASE NO. 2</th>
<th>SUBCLASSE &quot;STELIA&quot;</th>
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<tr>
<td>DESIGN VARIABLES SPECIFIC</td>
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<td>ALTITUDE [ft]</td>
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<tr>
<td>INLET total pressure (psia)</td>
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<tr>
<td>FULL PARAMETERS</td>
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<td></td>
</tr>
<tr>
<td>RAPIDITY [ft/min]</td>
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<td>1200</td>
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<tr>
<td>OPERATIONAL TOTAL HEAD (psi)</td>
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<tr>
<td>PROPELLER PARAMETERS</td>
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<td>ALUMINUM</td>
<td>STEEL</td>
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<td>1200</td>
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<tr>
<td>NPSH [PSI]</td>
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<td>10</td>
</tr>
<tr>
<td>A [Ft]</td>
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<td>10</td>
</tr>
<tr>
<td>B [Ft]</td>
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<td>5</td>
</tr>
<tr>
<td>C [Ft]</td>
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<td>5</td>
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<tr>
<td>Y [Y]</td>
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TITLE: MINIMIZATION OF S-SVALUES OPTIMIZATION

PARAMETERS

VARIABLES

CONSTRAINTS

OBJECTIVE FUNCTION

INITIAL CONDITIONS

CONVERGENCE CRITERION

OPTIONS

RESULTS

ERRORS
**Optimization Results**

**Design Case No. 2**

**Subcase: "STELNK"**

**Design Variables Specified**

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<th>Value</th>
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<tr>
<td>W</td>
<td>0.5104</td>
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</thead>
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</tr>
<tr>
<td>Ambient Pressure</td>
<td>1 atm</td>
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</table>

**Full Parameters**

<table>
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<tr>
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<th>Value</th>
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</thead>
<tbody>
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<td>R</td>
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**Propeller Parameters**

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<tr>
<td>Material</td>
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**Selection Values**

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<tr>
<td>R</td>
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<tr>
<td>D</td>
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</table>

**Constraint Values**

<table>
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<tr>
<td>Min Cl</td>
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</tbody>
</table>
FINAL OPTIMIZATION INFORMATION

COJ = -2.323E7 + DC

DECISION VARIABLES: 60
CONSTRAINT VALUES (G-VECTORS):

31 = 1.033E0 0.000E+00 0.895E+00 0.985E+00 0.000E+00 0.000E+00

THERE ARE 2 VOLUME CONSTRAINTS
THERE ARE 0 VIOLATED CONSTRAINTS
THERE ARE 0 ACTIVE SLACK CONSTRAINTS
TERMINATION CRITERION: RATIO OF 1.0E11 LESS THAN DAMPING FOR 30 ITERATIONS
NUMBER OF ITERATIONS = 35
OBJECTIVE FUNCTION WAS EVALUATED 209 TIMES
CONSTRAINT FUNCTIONS WERE EVALUATED 209 TIMES
SUBROUTINE ANALIZ(ICLAC)
INTEGER ICLAC
REAL ETA0,WEIGHT,Aeward,DIA,R,PE,F01,RES,TC75R,V
1 RJ CLAR,JCLACN,RT5RCL,R75RCU,AEACD,AEACCU,TC75CL,TC75CU
2 FCWAL,ARACU,AEACDG,TC35RS,RJ
3 VR,ETAL,ETAM,FAD,UF,ACSRM,HCL,PATM
4 PMAT,PMATM,DIAM,ETAC,AEACRN,TC75MN,SC
5 C75R,R75R,KM,PK,TOE,PTEV,EELEP,REC,PDAEU
COMMON /GLOECM/ETA0,WEIGHT,Aeward,DIA,R,PE,F01,RES,TC75R,V,RJCLAC,
1 RJ CLAC,JCLAC,RT5RCL,AEACD,AEACCU,TC75CL,TC75CU,PGWBAL,ACN
2 AEACDG,TC35RS,RJ
COMMON /FADAM/VR,TC14,TAT,ETADV,ETMP,NCGRM,HCL,PATM,PMATV,
1 PMAT,PMATM,DIAM,ETAR,AEACMN,TC75MN,SC
THIS SUBROUTINE, COUPLED WITH COPIES/COMMON, CONSTITUTES ANALYSIS
METHOD FOR "DESIGN CASE 3" PROPELLER SELECTION PROBLEMS
INFLTR-INITIALIZATION PHASE
PI1=3.14159265
IF(NOT(ICLC<ICLAC,EC3)=0) GOTO 1

SET "DESIGN CASE 3" PARAMETERS
ENVIRONMENTAL
Temp=55.0
WATR=1.0905
MAIN=.00012817
PATM=1.1
Patie=2.47

PROPPELLER PARAMETERS
n=666
PMAT=5.0

FULL PARAMETERS
hT=6.25
TC=0.1175
ETAR=1.1025
NCSRM=1.0
HCL=19.0

SET DESIGN VARIABLES HELD FIXED FOR "DESIGN CASE 3"
PE=21251.6
EN I INPUT-INITIALIZATION PHASE

GO TO 3

EXECUTION PHASE

1 CONTINUE
IF (NOT.((I<CALC .EQ. 21)GC TO 2
CALL R .CAL(KI)
CALL CF75RA(FC75R)
CALL REY75R(FC75R, R75R)
CALL CEFPC(RJ, R75R, R75R, KI, KU)
CALL OFEPFR(KI, KU, ETAD)
CALL JONAR(RJ, RCAL, RJCUT)
CALL REYNAV(RJ, RC75R, RC75R)
CALL TFCNFZ, AEAUO, TC75R, AEAACU, TC75CL, TC75CL)
CALL BIPC(PI, PC, PMLB, P1ACAL)
CALL CAVCVNK(RK, AEA-prefix)
CALL SIRGK(KE, R75R, TCSTK)
CALL WTCALC(75R)

GO TO 3

2 CONTINUE

OUTPUT-RESULT PHASE

PE = ((150/80000) / 3)300000 /
TCEV = (180°/1000)*(180°/1000) / 300000
PETCV = (((10.0-TO)/(1.0-TO))+(FATR+FIDEV) + NOSCK )
QREC = ([40+100]/(1.0+100) ) / 300000
PCREQ = (20*PI*QREQ*N) / 330000
ETACSP = (((10.0-TO)/(1.0-TO)) + ((PE/NOSCK ) 330000 )/ETARR111
1 WRITE(6, 9000)
WRITE(6, 9001)
WRITE(6, 9903) TEMP, WTR, WAINU, FAIN, PIRRA, WAINW
WRITE(6, 9903) KI, TD, ETARR, NOSCK, K, HCL, DIALIN
WRITE(6, 9004) KZ
IFI .NOT.(PRCMAT .EQ. 1.0) GC TO 61
WRITE(*,900515)

81
GE TC 6C
CENTILE
IF (N01,PRomat,EC,2.0) GC TO 82
WRITE(*,900615)
82
GE TC 6C
CENTILE
IF (N01,PRomat,EC,3.0) GC TO 83
WRITE(*,900715)
83
GE TC 6C
CENTILE
IF (N01,PRomat,EC,4.0) GC TO 84
WRITE(*,900815)
84
GE TC 6C
CENTILE
IF (N01,PRomat,EC,5.0) GC TO 85
WRITE(*,900915)
85
CENTILE
WRITE(*,9010)
86
CENTILE
WRITE(*,9011)PE, V, N, OS, PD, VT, ESP, PJ, KT, K, ETA0, K75K, DIA,
1
WRITE(*,9012)DIALIM, AEAMN, TC75MN
WRITE(*,9013)FDEV, VK, QREC, N, FEREC
3 CONTINUE
RETURN
C
C MISCELLANEOUS FORMAT STATEMENTS
C
9000 FORMAT(*'1, OPTIMIZATION RESULTS -------- DESIGN CASE NO. 3 '*1,/
1
9001 FORMAT(*'DESIGN VARIABLES SPECIFIED: PE, V, Q, N, DIA '*1,/
9002 FORMAT(*'ENVIRONMENTAL PARAMETERS: TEMP (DEG F)*, 22X, '*1,/
1
9003 FORMAT(*'FULL PARAMETERS: *1, 13X, 'WAKE FRACTION', 21X, '*1,/
1
9004 FORMAT(*'FPROPELLER PARAMETERS: *1, 6X, 'NUMBER OF BLADES', 18X, '*1,/
9005 FORMAT(*'MATERIAL TYPE', 21X, '= CAST IRON', '*1,/
APPCC670
APPCC680
APPCC690
APPCC700
APPCC710
APPCC720
APPCC730
APPCC740
APPCC750
APPCC760
APPCC770
APPCC780
APPCC790
APPCC800
APPCC810
APPCC820
APPCC830
APPCC840
APPCC850
APPCC860
APPCC870
APPCC880
APPCC890
APPCC900
APPCC910
APPCC920
APPCC930
APPCC940
APPCC950
APPCC960
APPCC970
APPCC980
APPCC990
APPCC1000
APPCC1010
APPCC1020
APPCC1030
APPCC1040
APPCC1050
APPCC1060
APPCC1070
APPCC1080
APPCC1090
APPCC1100
APPCC1110
APPCC1120
APPCC1130
APPCC1140
APPCC1150
APPCC1160
APPCC1170
APPCC1180
APPCC1190
APPCC1200
APPCC1210
APPCC1220
APPCC1230
APPCC1240
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APPCC1280
APPCC1290
APPCC1300
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APPCC1330
APPCC1340
APPCC1350
APPCC1360
APPCC1370
APPCC1380
APPCC1390
APPCC1400
APPCC1410
APPCC1420
APPCC1430
APPCC1440
0.125 + 0.035 = 0.160

1.250 + 0.035 = 1.285

12.50 + 0.035 = 12.535
APPENDIX K

COPES OUTPUT--DESIGN CASE NO. 3
**OPTIMIZATION RESULTS**

**DESIGN CASE NO. 1**

**SUBPROGRAM *STAIRS***

<table>
<thead>
<tr>
<th>DESIGN VARIABLES SPECIFIED</th>
<th>ENVIRONMENTAL PARAMETERS</th>
<th>FULL PARAMETERS</th>
<th>PROPPELLER PARAMETERS</th>
<th>SELECTION VALUES</th>
<th>CONSTRAINT VALUES</th>
<th>PROPELLER FEATURES</th>
</tr>
</thead>
<tbody>
<tr>
<td>P.W.G.S:MILIA</td>
<td>TEMP (1000 F)</td>
<td>TARE FRACTION</td>
<td>NUMBER OF BLADES</td>
<td>PR  (HP)</td>
<td>MAX GAP (ft)</td>
<td>P/D</td>
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<td>DISTILLING FRACTION</td>
<td>AREA FRACTION</td>
<td>NUMBER OF PADDLES</td>
<td>C (ft)</td>
<td>MIN GAP (ft)</td>
<td>V (fps)</td>
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<td>DISTILLING EFFICIENCY</td>
<td>NERW PADDLE</td>
<td>NURSE PADDLE</td>
<td>P/D</td>
<td>MAX C.G. LBF</td>
<td>D (ft)</td>
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<td>WATER VAPORATION PRESSURE</td>
<td></td>
<td>SPARES LIMIT (FT)</td>
<td>HOLE (ft)</td>
<td>MIN C.G. (LBF)</td>
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**NUMBERS**

- 54,000
- 0.145
- 0.12

**MATERIALS**

- STAINLESS STEEL

**STANDARD**

- 3000.0

**CONSTRAINTS**

- MAX GAP (ft): 5.0
- MIN GAP (ft): 0.34
- MAX C.G. LBF: 2.0
- MIN C.G. (LBF): 0.34
- P/D: 2.0
- V (fps): 22.2
- D (ft): 2.0
- P/D: 1.0
- V (fps): 22.2
- D (ft): 2.0
- P/D: 1.0
FINAL OPTIMIZATION INFORMATION

END

DELETE VARIABLES (A-VARIABLES)
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20

CONSTRAINT VALUES (C-VARIABLES)
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20

THERE ARE 1 ACTIVITY CONSTRAINTS
CONSTRAINT NUMBERS ARE

THERE ARE 0 VIOLATED CONSTRAINTS
CONSTRAINT NUMBERS ARE

THERE ARE 0 ACTIVE SIDE CONSTRAINTS

TERMINATION CRITERIA
TEN CONSECUTIVE ITERATIONS FAILED TO PRODUCE A FEASIBLE DESIGN
NUMBER OF ITERATIONS = 10

OBJECTIVE FUNCTION WAS EVALUATED 37 TIMES
CONSTRAINT FUNCTIONS WERE EVALUATED 37 TIMES
**Optimization Results**

**Case No. 3**

<table>
<thead>
<tr>
<th>Subroutine <em>KRAK</em></th>
</tr>
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</table>

**Design Variables Specified: Re: Y, L, M, O, X, A**

<table>
<thead>
<tr>
<th>Environmental Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Re, Y, L, M, O, X, A</td>
<td></td>
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<tr>
<td>Water viscosity (in Pa)</td>
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</tbody>
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** Hull Parameters: **

<table>
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<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>vielleicht</td>
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<tr>
<td>Weight (in kg)</td>
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<td>Center of gravity (in m)</td>
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</tbody>
</table>

**Propeller Parameters: **

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>Number (of blades)</td>
<td></td>
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<tr>
<td>Material (in kg)</td>
<td></td>
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<td>Allowable stress (in Pa)</td>
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</tbody>
</table>

**Selection Values: **

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>Re</td>
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**Constraint Values: **

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<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>Max ClA (in m)</td>
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<td>Max Y</td>
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**Propeller Values: **

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<th>Parameter</th>
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<tr>
<td>Re (in m/s)</td>
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<td>Y (in m/s)</td>
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<td>M (in m/s)</td>
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<td>X (in m/s)</td>
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<td>A (in m/s)</td>
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COPE5

GENERAL PROGRAM FOR ENGINEERING SYNTHESIS

TITLE
HAGENBERGER B-SERIES PROPELLER OPTIMIZATION
<table>
<thead>
<tr>
<th>CASE</th>
<th>IMAGE</th>
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FINAL OPTIMIZATION INFORMATION

CBR = 0.045454545

decision variables (x-vector)
-0.61235452 x 0.5120000
constraint values (z-vector)
-0.45235452 x 0.21345452

there are 0 violated constraints
there are 0 active side constraints
termination criterion
2.00000000 < max bound for 30 iterations

number of iterations = 46
objective function was evaluated 102 times
constraint functions were evaluated 102 times
**Optimization Results**

**Objective Function**

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**Design Variables**

**Design Constraints**

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| 4.  | 3      | Professor G.N. Vanderplaats, Code 69Vn  
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