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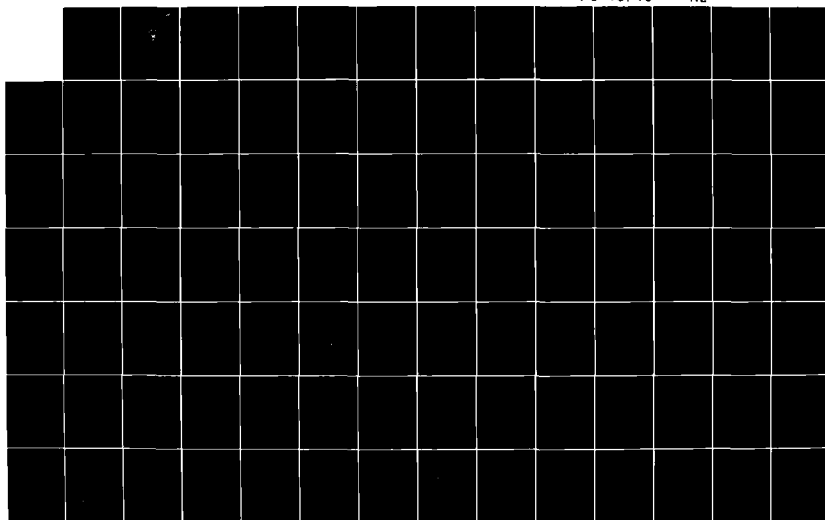
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B-SCREW SERIES AND A GENERAL PURPOSE NON-LINEAR
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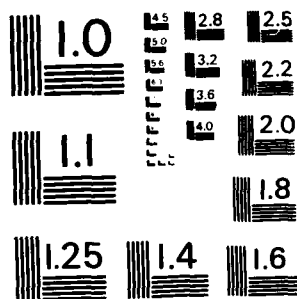
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PRELIMINARY PROPELLER SELECTION USING THE
WAGENINGEN B-SCREW SERIES AND A
GENERAL PURPOSE NON-LINEAR OPTIMIZER

by

Michael Peter Smith II

June 1983

Thesis Advisors:

D. Salinas

G. N. Vanderplaats

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REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER	2. GOVT ACCESSION NO. A132 414	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) Preliminary Propeller Selection Using the Wageningen B-Screw Series and a General Purpose Non-Linear Optimizer		5. TYPE OF REPORT & PERIOD COVERED Master's Thesis; June 1983
7. AUTHOR(s) Michael Peter Smith II		6. PERFORMING ORG. REPORT NUMBER
9. PERFORMING ORGANIZATION NAME AND ADDRESS Naval Postgraduate School Monterey, California 93940		8. CONTRACT OR GRANT NUMBER(s)
11. CONTROLLING OFFICE NAME AND ADDRESS Naval Postgraduate School Monterey, California 93940		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)		12. REPORT DATE June 1983
		13. NUMBER OF PAGES 362
		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE
16. DISTRIBUTION STATEMENT (of this Report) Approved for public release; distribution unlimited.		
17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)		
18. SUPPLEMENTARY NOTES		
19. KEY WORDS (Continue on reverse side if necessary and identify by block number) Wageningen propeller FORTRAN propeller strength design optimization propeller selection ship powering		
20. ABSTRACT (Continue on reverse side if necessary and identify by block number) 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		

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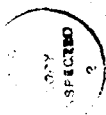
(20. ABSTRACT Continued)

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- 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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Preliminary Propeller Selection Using the
Wageningen B-Screw Series and a
General Purpose Non-Linear Optimizer

by

Michael Peter Smith II
Lieutenant, United States Naval Reserve
B.S., St. John Fisher College, 1971
B.S.E., The University of Michigan, 1976

Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN MECHANICAL ENGINEERING

from the

NAVAL POSTGRADUATE SCHOOL

June 1983

Author:

Michael P. Smith II

Approved by:

Robert N. Van Dyke

Thesis Advisor

David Salinas

Thesis Advisor

H. J. Martin

Chairman, Department of Mechanical Engineering

John Dyer

Dean of Science and Engineering

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:

- 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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ACKNOWLEDGEMENTS

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:

My mother and father, who provided, among other things, a secure and stable home for me to grow up in and who always insisted that I fulfill my potential for formal education at every opportunity.

My brothers and sister, who have always offered me nothing but praise and encouragement in all of the tasks that I have ever set out to do.

My aunts and uncles, living and deceased, who provided the counseling or the little "envelope for a rainy day" when I needed it the most.

My grandparents, now deceased, who possessed the courage and forethought to venture forth across an ocean to our great country in order to build a better life for themselves and to afford their offspring opportunities of a lifetime.

My close friends, past teachers, instructors and professors, who always pointed me in the right direction with astute guidance and timely advice when all seemed lost.

That one junior Naval officer, who was not afforded the opportunity to achieve the milestone represented by this

work because he maintained "the watch" for a shipmate like me.

And, finally, to You.

On a more current and professional note, I especially thank Dr. Marto, Professor Salinas, Professor Vanderplaats and also LCDR Michael R. Maixner, USN. Their patience, understanding and tireless efforts in helping me close out my academic career on a successful note are deeply appreciated and will always be remembered.

And a special word of thanks to Mr. Robert Lande for the expeditious and accurate typing of this thesis.

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

TRADITIONAL DESIGN SPIRAL

LBP, L/B , B/H , C_P , C_X

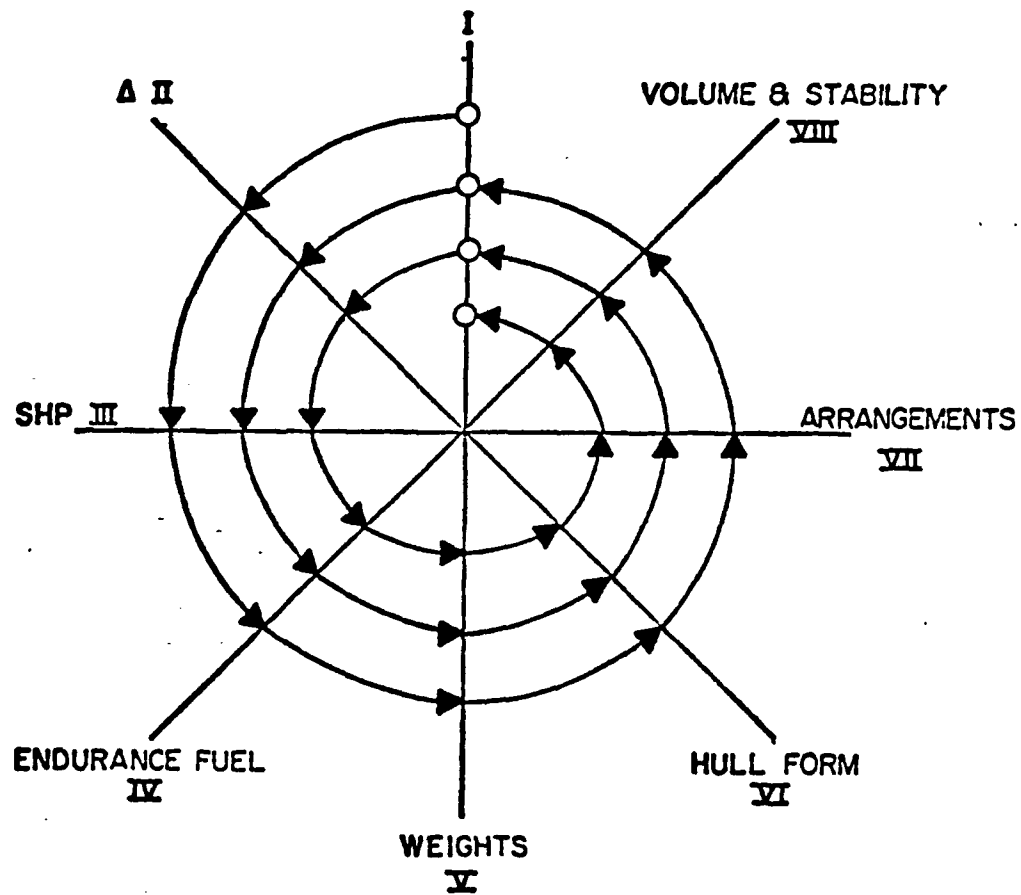


Figure 1.1 Traditional Design Spiral

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 " $Bp-\delta$ " and " $Bu-\delta$ " 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-sided 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:

$$\bar{D} = \begin{pmatrix} D_1 \\ \vdots \\ D_p \end{pmatrix} \quad (2.1)$$

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 $\bar{D}$. 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 $\bar{X}$ containing "n" components ($n \leq p$), each of which is associated with a design variable. That is:

$$\bar{X} = \begin{Bmatrix} x_1 \\ \vdots \\ x_n \end{Bmatrix} \quad (2.2)$$

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:

$$x_i^{\text{lower}} \leq x_i \leq x_i^{\text{upper}} \quad i = 1, \dots, n \quad (2.3)$$

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:

$$G_j(\bar{D}) \leq 0 \quad j = 1, \dots, m \quad (2.4)$$

Alternatively, the relation may be an equality on the "k"th of "l" equality constraints expressed as:

$$H_k(\bar{D}) = 0 \quad k = 1, \dots, l \quad (2.5)$$

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:

$$\begin{aligned} G_j(\bar{X}) &\leq 0 & j &= 1, \dots, m \\ H_k(\bar{X}) &= 0 & k &= 1, \dots, l \end{aligned} \quad (2.6)$$

$$x_i^{\text{lower}} \leq x_i \leq x_i^{\text{upper}} \quad i = 1, \dots, n$$

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:

$$\begin{aligned}
 \text{Minimize:} \quad & F(\bar{D}) = \text{OBJ} \\
 \text{Subject to:} \quad & G_j(\bar{D}) \leq 0 \quad j = 1, \dots, m \quad (2.7) \\
 & H_k(\bar{D}) \leq 0 \quad k = 1, \dots, \ell \\
 & x_i^{\text{lower}} \leq x_i \leq x_i^{\text{upper}} \quad i = 1, \dots, n
 \end{aligned}$$

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:

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

$$\text{Subject to: } G(\bar{X}) \leq 0 \quad j = 1, \dots, m \quad (2.8)$$

$$H_k(\bar{X}) = 0 \quad k = 1, \dots, \ell$$

$$x_i^{\text{lower}} \leq x_i \leq x_i^{\text{upper}} \quad i = 1, \dots, n$$

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:

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

$$\text{Subject to: } G_j(\bar{X}) \leq 0 \quad j = 1, \dots, m \quad (2.9)$$

$$x_i^{\text{lower}} \leq x_i \leq x_i^{\text{upper}} \quad i = 1, \dots, n$$

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 $H_k(\bar{X}) = 0$, 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^{lower} and x_i^{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, $F(\bar{X}) = \text{OBJ}$, 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:

$$\bar{X}^{(q+1)} = \bar{X}^{(q)} + \alpha^* \bar{S}^{(q)} \quad (2.10)$$

the optimization process continues by following the constraint boundaries in a direction of search $\bar{S}$ so that the value of $F(\bar{X})$ decreases with each iteration q . The scalar α^* defines the distance of travel in the direction of search $\bar{S}$. 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:

$$P_E = \frac{R_T V}{550} \quad (3.1)$$

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:

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

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:

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

4) Shaft Horsepower (P_S)--power delivered to the inboard side of the stern tube having a transmission efficiency of η_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:

$$\bar{P}_B = \frac{P_S}{\eta_B \eta_G} \quad (3.5)$$

where η_B and η_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

$$(1-td) = \frac{R_T}{T} \quad (3.6)$$

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:

$$(1-wt) = \frac{V_A}{V} \quad (3.7)$$

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

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

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 ρ . 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 ρ . 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 (η_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 (η_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 (η_R)--the ratio of the actual, behind-hull efficiency to the open water efficiency. The value of η_R does not, in general, depart from the value

of 1.0. Most often, η_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 ρ is a property of the fluid in which the hull and propeller operate. And, finally, η_B, η_G and η_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:

$$P_E = \frac{(1-td)}{(1-wt)} \cdot \eta_R \eta_O P_D \quad (3.13)$$

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

$$\frac{R_T V}{550} = \frac{(1-td)}{(1-wt)} \cdot \eta_R \eta_O \cdot \frac{2\pi Q_S n_P}{550} \quad (3.14)$$

Rearranging terms of equation (3.14) gives:

$$\frac{R_T}{(1-td)} \cdot \frac{(1-wt)V}{550} = \eta_R \eta_O \cdot \frac{2\pi Q_S n_P}{550} \quad (3.15)$$

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

$$\frac{T V_A}{550} = \frac{T(1-wt)V}{550} = \eta_R \eta_O \cdot \frac{2\pi Q_S n_P}{550} \quad (3.16)$$

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 w_t and t_d 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 (η_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 (η_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 (η_o) is now established as a requirement to be met. The objective is, simply, to select a propeller whose open water efficiency (η_o), 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 ρ and kinematic viscosity ν) 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 (η_o)

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_O), 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.

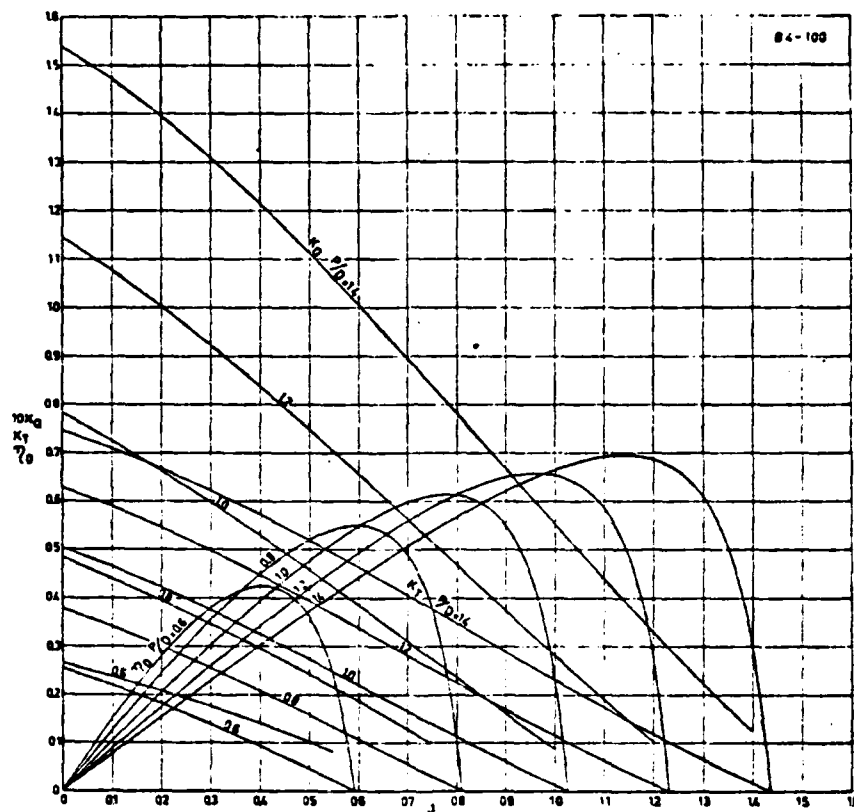


Figure 3.1 Open Water Test Results--B 4-100 Series Propeller

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_0 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

Blade number Z	Blade area ratio A_E/A_0														
2	0.30														
3		0.35			0.50			0.65			0.80				
4			0.40			0.55		0.70				0.85		1.00	
5				0.45			0.60		0.75						1.05
6					0.50			0.65			0.80				
7						0.55			0.70			0.85			

2. Series Results

The test results of the Wageningen B-Screw Series were originally presented in the form of $B_p-\delta$, $B_u-\delta$ 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 (η_o), 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.

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

$$K_T = f_1(J, P/D, A_E/A_O, Z, t^*/c_{.75R}) \quad (3.17)$$

$$K_Q = f_2(J, P/D, A_E/A_O, Z, t^*/c_{.75R})$$

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

$$K_T = K'_T + \Delta K_T \quad (3.18)$$

$$K_Q = K'_Q + \Delta K_Q$$

The polynomial expressions found in Tables (5) and (6) of Reference [2] are then used to evaluate the components K'_T , K'_Q , ΔK_T and ΔK_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 2×10^6 . It is defined as:

$$Rn_{.75R} = \frac{c_{.75R} \sqrt{(V_A)^2 + (0.75\pi n_P D^2)}}{v} \quad (3.19)$$

where:

- v = kinematic viscosity of the fluid (ft²/sec);
- $c_{.75R}$ = blade section chord length at 3/4 propeller radius (.75R) in feet (ft).

To account for "other effects", coefficients ΔK_T and ΔK_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 2×10^6 . 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 ($Rn^*_{.75R}$) given by:

$$Rn^*_{.75R} = \exp \left[4.6052 + \left\{ \sqrt{\frac{1+2(t/c)_{.75R}}{1+2(t^*/c)_{.75R}}} (\ln Rn_{.75R} - 4.6052) \right\} \right] \quad (3.20)$$

where:

- $Rn^*_{.75R}$ = the new equivalent Reynolds number;
- $(t^*/c)_{.75R}$ = new equivalent t/c at 3/4 propeller radius;
- $Rn_{.75R}$ = 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:

$$t/c_{.75R} = \frac{(0.0185 - 0.00125Z)Z}{2.073 A_E/A_0} \quad (3.21)$$

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,

$$Z = 2, 3, 4, 5, 6 \text{ or } 7 \quad (3.22)$$

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:

$$2 \times 10^6 \leq Rn_{.75R} \leq 2 \times 10^9 \quad (3.23)$$

If the equivalent t/c is varied from the standard equivalent value $(t/c)_{.75R}$, then the new equivalent Reynolds number $(Rn^*_{.75R})$, which results from this variation, must lie within the same limits. That is,

$$2 \times 10^6 \leq Rn^*_{.75R} \leq 2 \times 10^9 \quad (3.24)$$

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

- a) $wt = .22$
- b) $V = 20$ (knots)
- c) $N_p = 104$ (rpms)
- d) $D = 25$ (ft)
- e) $c_{.75R} = 4.0$ (ft)
- f) $v = 1.2285 \times 10$ (ft²/sec)

the value for $Rn_{.75R}$ is equal to 3.619×10^7 .

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

$$0.4 \leq P/D \leq 1.4 \quad (3.25)$$

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

$$0 < J \leq 1.6 \quad (3.26)$$

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_{lim}). As a constraint on a selected propeller of diameter D , this may be written as:

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

or, alternatively, as:

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

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_O 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_{watvap}) 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 ($A_E/A_O \min$) to avoid cavitation and is given by:

$$(A_E/A_O)_{\min} = \frac{(1.3 + 0.3Z)}{(P_{\text{atm}} + \rho \cdot \text{acg} h_{\text{cl}} - P_{\text{watvap}})} \cdot \frac{T}{D^2} + b \quad (4.3)$$

where:

- Z = number of blades;
- T = developed thrust (lbf);
- D = propeller diameter (ft);
- P_{atm} = atmospheric pressure (psia);
- P_{watvap} = fluid vaporization pressure (psia)
- ρ = fluid density (lbf sec²/ft⁴)
- acg = 32.174 (ft/sec²)
- h_{cl} = 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:

$$(A_E/A_O)_{\min} \leq A_E/A_O \quad (4.4)$$

or

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

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:

$$t_{min}^*/c = (t^*/c)_{min} \leq t^*/c \quad (4.6)$$

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:

$$(t^*/c)_{.75R \text{ min}} \leq (t^*/c)_{.75R} \quad (4.7)$$

or

$$G_{11}(\bar{X}) = \frac{(t^*/c)_{.75R \text{ min}}}{(t^*/c)_{.75}} - 1 \leq 0 \quad (4.8)$$

Reference [2] suggests the following empirical relation for the minimum required equivalent blade section maximum thickness-to-chord ratio $(t^*/c)_{.75R \min}$:

$$(t^*/c)_{.75R \min} = \frac{z \left\{ 0.0028 + 0.21 \sqrt[3]{\frac{(2375 - 1125P/D) P_D}{4.123 N_P D^3 (S_C + \frac{D^2 N_P^2}{12.788})}} \right\}}{2.073 A_E/A_O} \quad (4.9)$$

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 $\bar{D}$ 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 ($^{\circ}\text{F}$)--Temp
- 2) fluid density ($\text{lbf sec}^2/\text{ft}^4$)-- ρ
- 3) fluid viscosity (ft^2/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 -- η_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
Material Identifier Reference

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

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).

$$\begin{array}{c}
 \bar{X} = \left\{ \begin{array}{l} P_E \\ V \\ D \\ P/D \\ A_E/A_O \\ (t^*/c) .75R \\ N_P \\ Q_S \end{array} \right\}
 \end{array}
 \begin{array}{c}
 \bar{D} = \left\{ \begin{array}{l} \text{Temp} \\ \rho \\ v \\ P_{\text{watvap}} \\ P_{\text{atm}} \\ wt \\ td \\ \eta_R \\ \text{noscw} \\ h_{cl} \\ D_{lim} \\ z \\ \text{promat} \\ P_E \\ V \\ D \\ P/D \\ A_E/A_O \\ (t^*/c) .75R \\ N_P \\ Q_S \end{array} \right\}
 \end{array}$$

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:

$$1 \leq \frac{Rn^* \cdot 75R}{2 \times 10^6} \leq 1000 \quad (4.10)$$

Two constraints are derived:

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

$$G_4(\bar{X}) = \frac{Rn^* \cdot 75R}{2 \times 10^6} - 1000 \leq 0 \quad (4.12)$$

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

$$(A_E/A_O)_{\text{lower}}(Z) \leq A_E/A_O \leq (A_E/A_O)_{\text{upper}}(Z) \quad (4.13)$$

Two constraints are derived:

$$G_5(\bar{X}) = (A_E/A_O)_{\text{lower}}(Z) - A_E/A_O \leq 0 \quad (4.14)$$

$$G_6(\bar{X}) = A_E/A_O - (A_E/A_O)_{\text{upper}}(Z) \leq 0 \quad (4.15)$$

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 (η_o), given by equation (3.11), be maximized. In terminology related to optimization, this is stated as:

$$\text{OBJ}_{1,2} = -\eta_0 \quad (4.22)$$

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:

$$\text{Minimize: } F(\bar{X}) = \text{OBJ}_{1,2} \text{ or } \text{OBJ}_3 \quad (4.24)$$

$$\text{Subject to: } G_j(\bar{X}) \leq 0 \quad j = 1, \dots, 12$$

$$x_i^{\text{lower}} \leq x_i \leq x_i^{\text{upper}} \quad i = 1, \dots, 8$$

The constraint $G_{12}(\bar{X})$ and the values for x_i^{lower} and x_i^{upper} 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 III

Global Common (GLOBCM) Catalog

Global Location	FORTTRAN Name	DEFINITION
1	ETAO	η_o
2	WEIGHT	bldwt
3	AEDVAO	A_E/A_O
4	DIA	D
5	N	$N_P = 60 \cdot n_P$
6	PE	P_E
7	PDIVD	P/D
8	QS	Q_S
9	TC75R	$(t^*/c)_{.75R}$
10	V	V (ft/sec)
11	RJCHL	$G_1(\bar{X})$ --eqn (4.17)
12	RJCNU	$G_2(\bar{X})$ --eqn (4.18)
13	R75RCL	$G_3(\bar{X})$ --eqn (4.11)
14	R75RCU	$G_4(\bar{X})$ --eqn (4.12)
15	AEAOCL	$G_5(\bar{X})$ --eqn (4.14)
16	AEAOUCU	$G_6(\bar{X})$ --eqn (4.15)
17	TC75CL	$G_7(\bar{X})$ --eqn (4.20)
18	TC75CU	$G_8(\bar{X})$ --eqn (4.21)
19	POWBAL	$G_{12}(\bar{X})$ --eqn (7.10) or (8.11) or (9.4)
20	DIACNU	$G_9(\bar{X})$ --eqn (4.2) or (9.6)
21	AEAOVCV	$G_{10}(\bar{X})$ --eqn (4.5)
22	TCSTRS	$G_{11}(\bar{X})$ --eqn (4.8)
23	RJ	J

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 ($-\eta_o$ 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 COEFSR--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 (η_o) 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_O) 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 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 WGTCAL 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 $r = .167R$ to $r = R$ for $Z = 4, 5, 6$ and $r = .18R$ to $r = R$ for $Z = 3, 7$. For convenience, a non-dimensional variable "x" will be defined as:

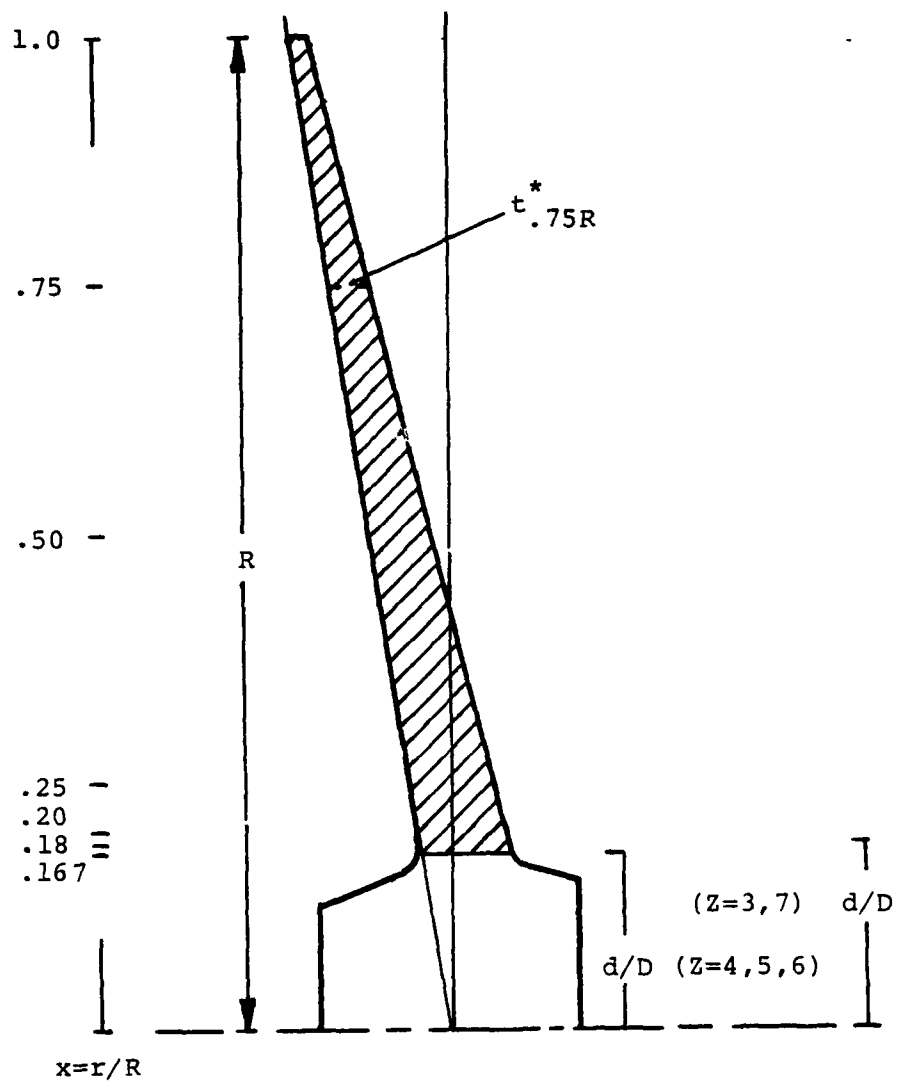


Figure 5.1 Propeller Blade & Hub--Side View

$$x = \frac{r}{R} \quad (5.1)$$

Limits are now expressed as $x = .167$ or $.18$ 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:

$$y_{fa} = V_1(t^* - t_{te}^*) \quad P \leq 0 \quad (5.2)$$

$$y_{ba} = (V_1 + V_2)(t^* - t_{te}^*) + t_{te}^* \quad P \leq 0 \quad (5.3)$$

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 = tabulated values depending on x and P
(see Tables (2) and (3), Ref. [2]);

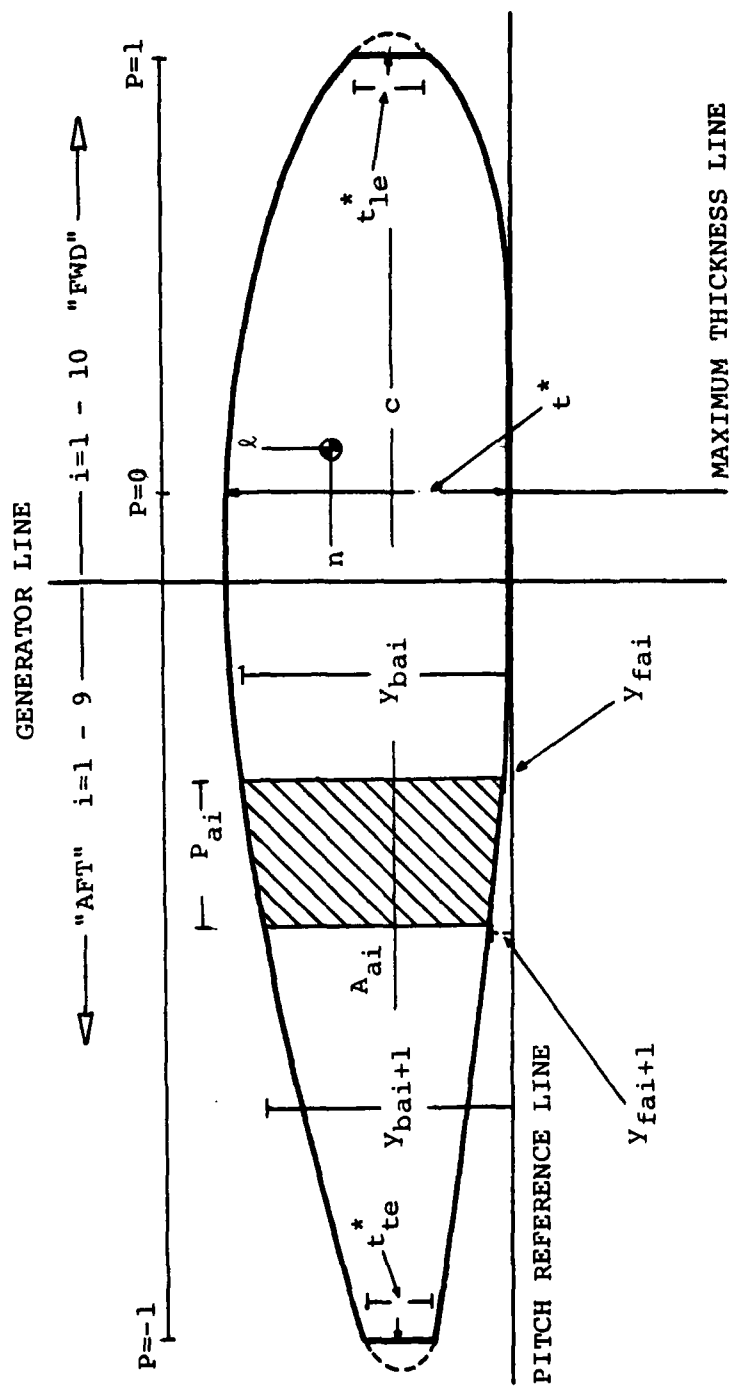


Figure 5.2 Expanded Cylindrical Blade Section--Profile View

t_{le}^* = blade section leading edge thickness (ft);

t_{te}^* = 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:

$$t_{le}^* = t_{te}^* = \left(\frac{1}{10}\right) t^* \quad (5.6)$$

3. Blade Section Cross-Sectional Area

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

$$A(x) = \sum_{i=1}^9 A_{ai} + \sum_{i=1}^{10} A_{fi} \quad (5.7)$$

where

$$A_{ai} = \Delta P_{ai} \left\{ \frac{h_{ai+1} + h_{ai}}{2} \right\} \quad (5.8)$$

$$h_{ai} = y_{bai} - y_{fai} \quad (5.9)$$

$$h_{ai+1} = y_{bai+1} - y_{fai+1} \quad (5.10)$$

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 ΔP_{ai} and ΔP_{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 (ft²). Units for h_{ai} , h_{ai+1} , h_{fi} , h_{fi+1} , c, ΔP_{ai} and ΔP_{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:

$$\text{bldwt} = \text{bldvol} \cdot \text{wd} \cdot 1728 \quad (5.11)$$

where:

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

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

C. CODING

SUBROUTINE WGTCAL 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 $.18R, .2R, .3R, .4R, \dots, .9R, 1.0R$), 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 WGTCAL.

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

[Ref. 8] 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. Aernoldus 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 $r = r_o$:

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

where:

- $[M]_{no}, [M]_{lo}$ = resultant bending moments in planes normal ($[M]_{no}$) and parallel ($[M]_{lo}$) to the strength section's chord at $r = r_o$ (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 (l-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:

$$[M]_{no} = [M_p]_{no} + [M_{cb}]_{no} \quad (6.2)$$

$$[M]_{lo} = [M_p]_{lo} + [M_{cb}]_{lo} \quad (6.3)$$

where:

$[M_p]_{no}$ = total bending moment due to hydrodynamic loading acting in a plane normal to a strength section's chord at $r = r_o$ (ftlbft);

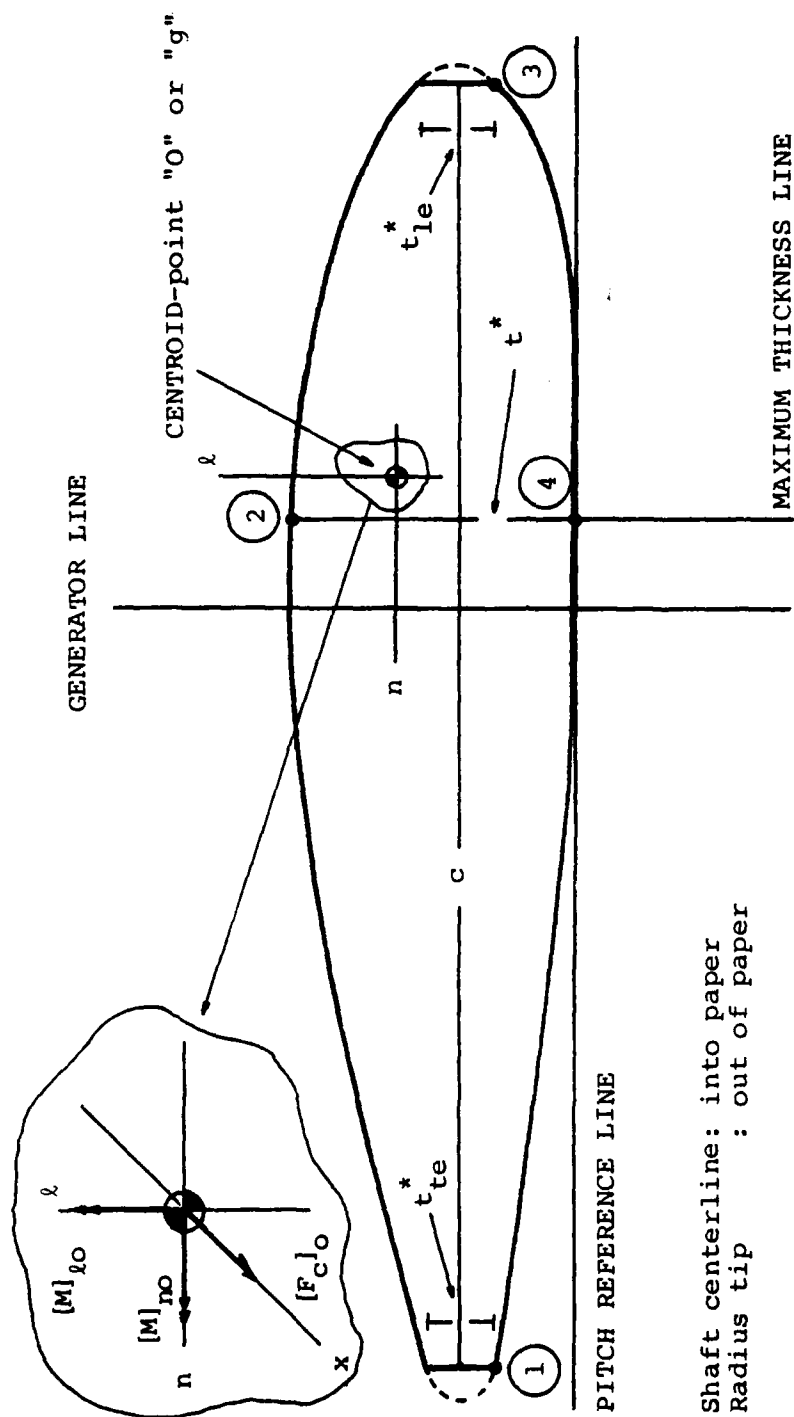
$[M_p]_{lo}$ = total bending moment due to hydrodynamic loading acting in a plane parallel to a strength section's chord at $r = r_o$ (ftlbft);

$[M_{cb}]_{no}$ = total bending moment due to centrifugal loading acting in a plane normal to a strength section's chord at $r = r_o$ (ftlbft);

$[M_{cb}]_{lo}$ = total bending moment due to centrifugal loading acting in a plane parallel to a strength section's chord at $r = r_o$ (ftlbft).

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,



Shaft centerline: into paper
 Radius tip : out of paper

Figure 6.1 Strength Section at $r = r_O$

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 hydrodynamic "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 expression for the bending moment due to thrust $([M_t]_o)$ which acts at a blade section located at radius $r = r_o$:

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

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 $x_o = r_o/R$ and $x_h = 0.2$ and given by equations (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:

$$[M_q]_o = \frac{Q_P}{Z} \cdot \frac{\psi_2(x_o)}{\phi_1(x_h)} \quad (6.5)$$

where:

Q_p = propeller torque (ft-lbf);
 Z = no. of blades;
 $\psi_2(x_o), \phi_1(x_h)$ = functions of non-dimensional radius x
 evaluated at $x_o = r_o/R$ and $x_h = 0.2$
 and given by equations (19) and (4).

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

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

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

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 $[M_{cb}]_{lo}$ 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

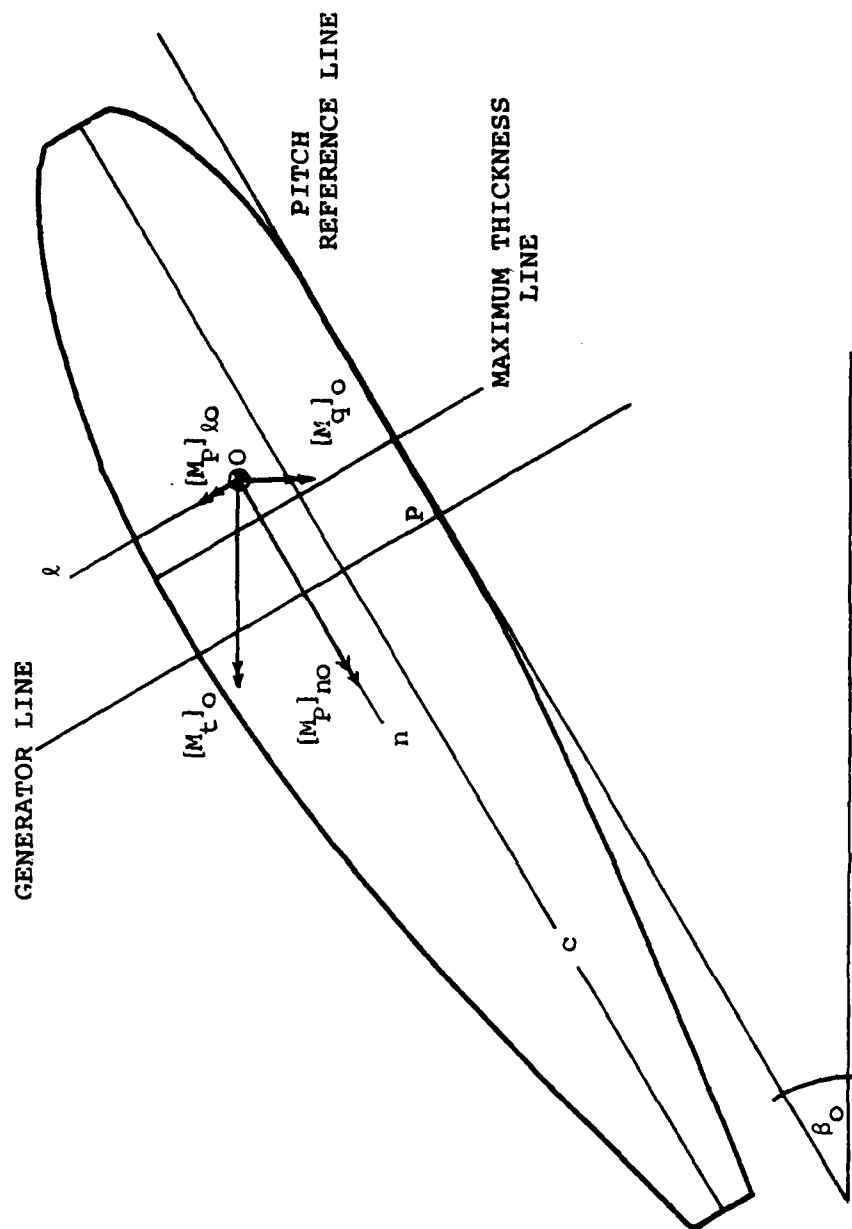


Figure 6.2 Bending Moments due to Thrust and Torque

method, $[M_{cb}]_{n_0}$ and $[M_{cb}]_{l_0}$ 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 $x = x_0 = r_0/R$ 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 $x = x_0 = r_0/R$, and through point "G", which is the center of gravity of the blade element above the blade section at $x = x_0 = r_0/R$. From the figure, the following expression is derived:

$$[C_F]_O = [C_F]_O \cos \zeta(x_0) + [C_F]_O \sin \zeta(x_0) \quad (6.8)$$

$[C_F]_O$ is shifted to point "N" and is decomposed into components $[C_F]_O \cos \zeta(x_0)$ and $[C_F]_O \sin \zeta(x_0)$. The entire cylindrical surface in which the blade section at $x = x_0 = r_0/R$ and point "N" lie is now expanded into a flat plane for further consideration (see Figure (6.4)). In this configuration, $[C_F]_O \cos \zeta(x_0)$ is normal to this flat plane while $[C_F]_O \sin \zeta(x_0)$ 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:

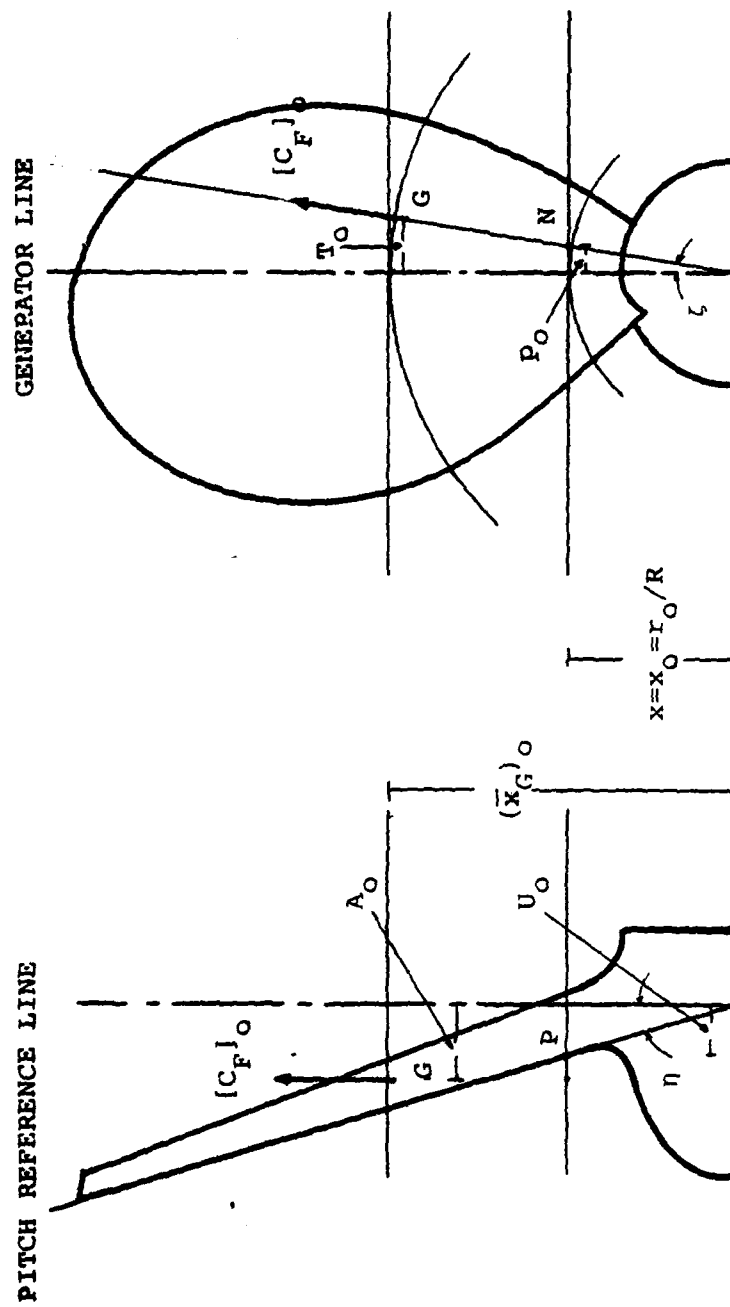
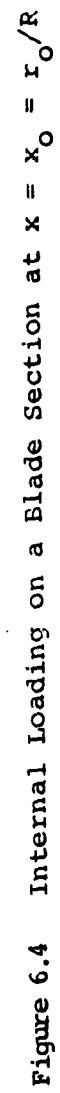


Figure 6.3 Center of gravity "G" and intersection point "N"



$$[F_c]_O = [C_F]_O \cos \zeta(x_O) \quad (6.9)$$

$$[D_c]_O = [C_F]_O \sin \zeta(x_O) \quad (6.10)$$

$$[M_{cb}]_O = [F_c]_O \cdot \overline{NO} \quad (6.11)$$

$$[M_{cw}]_O = [D_c]_O \cdot \overline{LO} \quad (6.12)$$

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 l - n axes system as follows:

$$[M_{cb}]_{no} = [C_F]_o \cos \zeta(x_o) \{p_o \sin \beta_o + q_o \cos \beta_o + Y_{co}\} \quad (6.13)$$

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

where:

β_o = pitch angle of the blade section at
 $x = x_o = r_o/R$;

X_{co} = distance of the blade sections centroid from
the generator line (ft);

Y_{co} = distance of the blade section's centroid from
the pitch reference line (ft);

q_o = distance to point "N" from point "P"
parallel to the shaft axis at $x = x_o = r_o/R$
(ft);

p_o = distance to point "N" from point "P"
perpendicular to the shaft axis at
 $x = x_o = r_o/R$ (ft).

The quantity β_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:

$$[C_F]_o = 1728 \cdot \frac{w d V_o}{acg} \cdot (2\pi n_p)^2 \cdot R \cdot (\bar{x}_G)_o \quad (6.16)$$

where:

- V_o = volume of the blade element above the blade section at $x = x_o = r_o/R$ (ft³);
 acg = 32.174 ft/sec²;
 wd = material weight density (lbf/in³);
 n_p = propeller revolution rate (rps);
 $(\bar{x}_G)_o$ = non-dimensional radial position of "G" for the blade element above the shaft axis;
 R = 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) $(\bar{x}_G)_o$
- 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

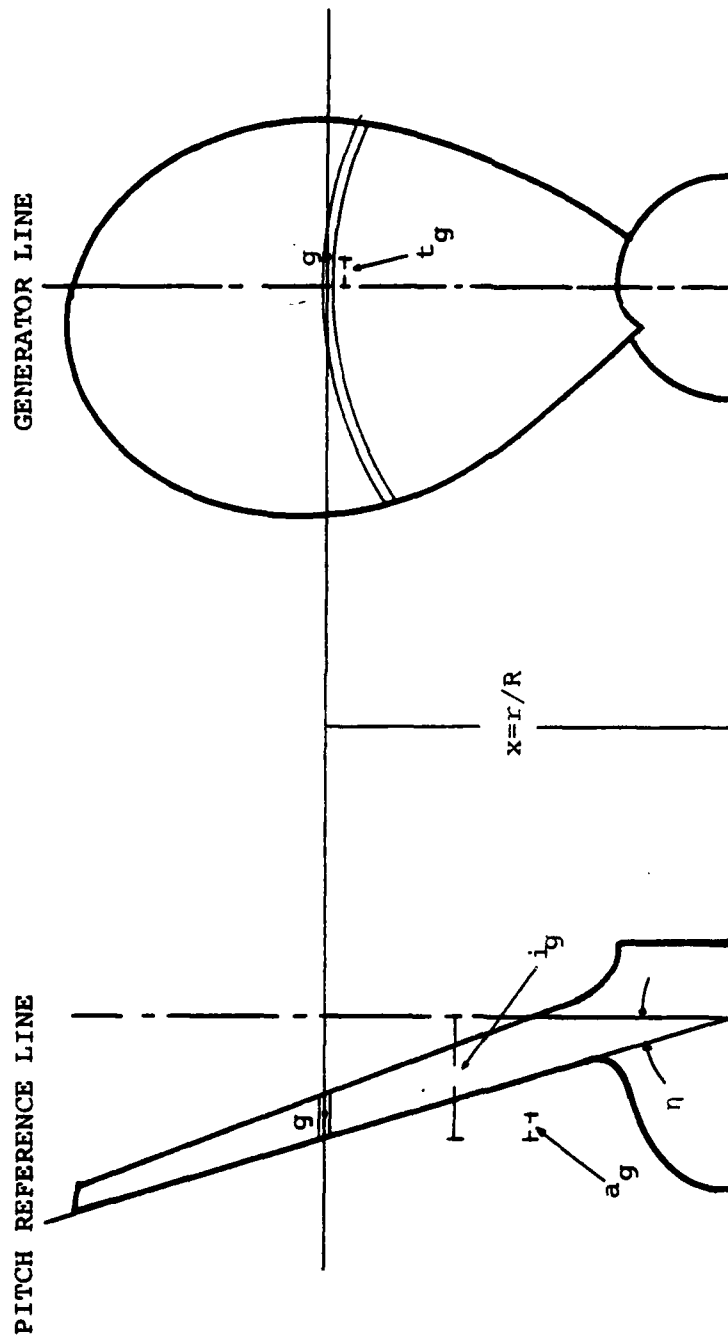


Figure 6.5 Position of " g " of a Blade Section "Slice" at $x = r/R$

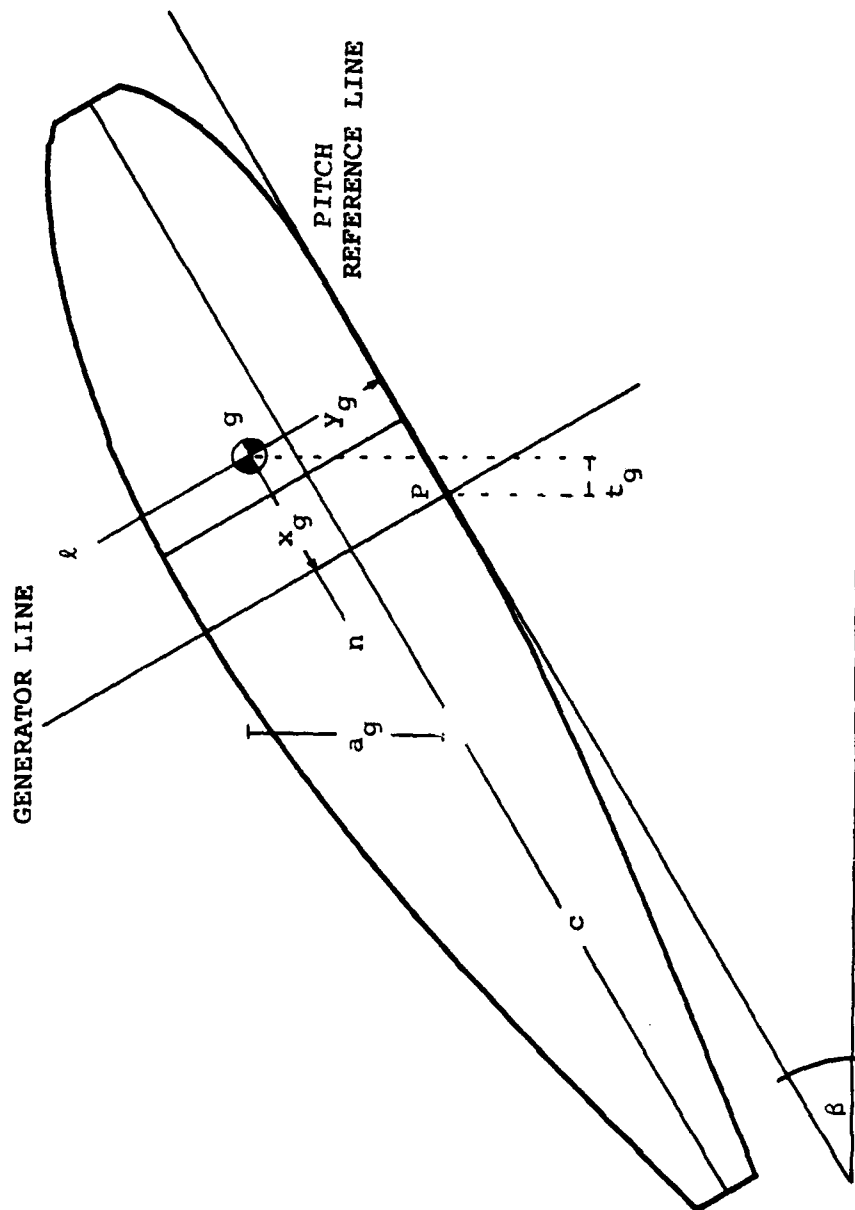


Figure 6.6 Coordinates of centroid "G" of any Blade Section

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:

$$i_g = x R \tan \eta \quad (6.17)$$

$$i_g - a_g = i_g - x_g \sin \beta_g - y_g \cos \beta_g \quad (6.18)$$

$$t_g = x_g \cos \beta_g - y_g \sin \beta_g \quad (6.19)$$

where:

η = rake angle at x ;

x_g = distance of "g" from point "P" parallel to the shaft axis (ft);

y_g = distance of "g" from point "P" perpendicular to the shaft axis (ft).

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

Now, to compute the volume of the blade element above the blade section located at $x = x_0 = r_0/R$, the following expression is used:

$$V_0 = \int_{x=x_0}^1 RA(x) dx \quad (6.20)$$

To compute the non-dimensional radial position of "G" for the blade element above a blade section located at $x = x_0 = r_0/R$, the following expression is used:

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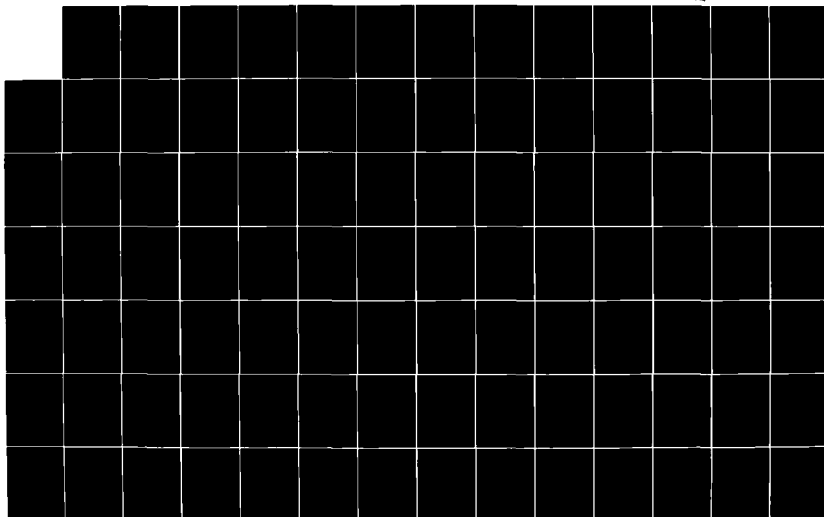
PRELIMINARY PROPELLER SELECTION USING THE WAGENINGEN
B-SCREW SERIES AND A GENERAL PURPOSE NON-LINEAR
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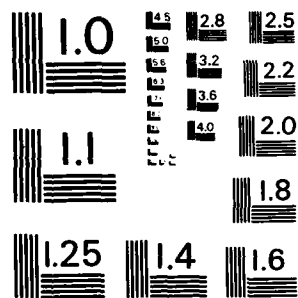
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$$(\bar{x}_G)_O = \frac{\int_{x=x_O}^1 A(x) x dx}{\int_{x=x_O}^1 A(x) dx} \quad (6.21)$$

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:

$$T_O = \frac{\int_{x=x_O}^1 A(x) t_g dx}{\int_{x=x_O}^1 A(x) dx} \quad (6.22)$$

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:

$$A_O = \frac{\int_{x_O}^1 A(x) (i_g - a_g) dx}{\int_{x_O}^1 A(x) dx} \quad (6.23)$$

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 :

$$p_O = \frac{x_O}{(\bar{x}_G)_O} T_O \quad (6.24)$$

$$q_0 = A_0 - x_0 \tan \eta \quad (6.25)$$

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

$$\cos \zeta(x_0) = \frac{p_0}{x_0 R} \quad (6.26)$$

The formulation is now complete. Equations (6.10), (6.13) and (6.14) can now be evaluated for any blade section located at $x = x_0 = r_0/R$. 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 (u_1, w_1) , (u_2, w_2) , (u_3, w_3) and (u_4, w_4) , at any location $x = x_0 = r_0/R$.

From the development discussed in Chapter V, the values for $A(x)$, x_g , y_g , I_{n0} and I_{l0} 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 $((t^*/c)_{.75R \min})$ for use in the constraint $G_{11}(\bar{X}) \leq 0$ given by equation (4.8). The procedure employed is as follows:

- 1) assume an initial value for $(t^*/c)_{.75R \min}$ using equation (3.21);
- 2) increase this value by a small amount;

3) using $(t^*/c)_{.75R \text{ min}}$ 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 $[M_p]_{no}$ and $[M_p]_{lo}$ at radius locations just specified;

6) compute the values of the centrifugal force $[F_c]_o$ and the bending moment components $[M_{cb}]_{no}$ and $[M_{cb}]_{lo}$ 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_{min}^*) for the assumed value of $(t^*/c)_{.75R_{min}}$;

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, $r = .2R, .3R, .4R, .5R, .6R, .7R, .8R$ and $.9R$). 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 $\bar{X}$

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 $\bar{X}$ (see Figure 4.1) to:

$$\bar{X} = \begin{pmatrix} D \\ P/D \\ A_E/A_O \\ (t^*/c) .75R \\ N_P \\ Q_S \end{pmatrix} \quad (7.1)$$

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 (η_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:

$$\bar{X} = \begin{pmatrix} D \\ P/D \\ A_E/A_O \\ (t^*/c) \cdot .75R \\ N_P \end{pmatrix} \quad (7.4)$$

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:

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

2. Powering Constraint

Having determined the design vector $\bar{X}$, 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 $\bar{X}$, 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:

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

From equation (3.9), it follows that:

$$(P_T)_{dev} = \frac{\rho n_P^2 D^4 K_T}{550} \cdot V(1-wt) \quad (7.7)$$

Using equation (3.12), the developed thrust horsepower can be defined in terms of developed effective horsepower given by:

$$(P_E)_{dev} = \frac{(1-t_d)}{(1-w_t)} \cdot (P_T)_{dev} \quad (7.8)$$

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

$$P_E \leq (P_E)_{dev} \quad (7.9)$$

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

$$G_{12}(\bar{X}) = 1 - \frac{(P_E)_{dev}}{P_E} \leq 0 \quad (7.10)$$

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

$$\begin{aligned} \text{Maximize:} \quad & F(\bar{X}) = \text{OBJ}_{1,2} \\ \text{Subject to:} \quad & G_j(\bar{X}) \leq 0 \quad j = 1, \dots, 12 \\ & x_{i, \text{lower}} \leq x_i \leq x_{i, \text{upper}} \quad i = 1, \dots, 5 \end{aligned} \quad (7.11)$$

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) $wt = .22$
- 3) $td = .19$
- 4) $\eta_R = 1.025$
- 5) $noscrw = 1$
- 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:

$$\overline{XT} = \begin{Bmatrix} J \\ P/D \end{Bmatrix}$$

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

$$P/D = 1.1651$$

$$N_p = 104 \text{ (rpm)}$$

$$P_D = 25544 \text{ (hp)}$$

$$\eta_o = .6676$$

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

$$J = .8286$$

$$Q_S = 1290000.0 \text{ (ft-lbf)}$$

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 $\overline{XT}$ (NDV = 2) is used in both cases. One variation uses SUBROUTINE STRCNA to evaluate the constraint $G_{12}(\overline{XT})$ given by equation (4.8). The other uses SUBROUTINE STRCNK to determine $G_{12}(\overline{XT})$.

The remaining two variations will solve the propeller selection problem using the design vector $\overline{XI}$ (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) $v = 1.2285 \cdot 10 \text{ (ft}^2/\text{sec)}$

- 4) $p_{\text{watvap}} = .247$ (psia)
- 5) $p_{\text{atm}} = 14.7$ (psia)
- 6) $wt = .22$
- 7) $td = .19$
- 8) $\eta_R = 1.025$
- 9) $\text{noscw} = 1$
- 10) $h_{c_l} = 19.0$ (ft)
- 11) $D_{\text{lim}} = 22.0$ (ft)
- 12) $z = 5$
- 13) $\text{promat} = 5$ (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 ($\text{ICALC} = 1$) of each SUBROUTINE ANALIZ pertaining to each variation.

The constraint $G_{12}(\overline{X_I})$ or $G_{12}(\overline{X_T})$ 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 $\overline{X_T}$, the following design variables of $\overline{X_I}$ become parameters and are specified in the input section of SUBROUTINE ANALIZ ($\text{ICALC} = 1$) as:

- 1) $D = 22.0$ (ft)
- 2) $A_E/A_O = .85$
- 3) $(t^*/c)_{.75R} = .0348$ (from equation 3.21).

For constraints, the following are used:

$$G_j(\overline{XT}) \leq 0 \quad j = 1, \dots, 8, 12$$

Only nine of twelve constraints are evaluated (NCON = 9). Obviously, some of the twelve constraints are redundant since D , A_E/A_0 , and $(t^*/c)_{.75R}$ have been specified.

The upper (XT_i^{upper}) and lower (XT_i^{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 (XT_i) 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 $\bar{X}$. For constraints, the following are used:

$$G_j(\bar{X}) \leq 0 \quad j = 1, \dots, 12$$

All twelve constraints are evaluated (NCON = 12).

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

$$1.0 \leq D \leq 50.0 \text{ (ft)}$$

$$.4 \leq P/D \leq 1.4$$

$$.2 \leq A_E/A_O \leq 1.1$$

$$.003 \leq (t^*/c)_{.75R} \leq .50$$

$$.01 \leq J \leq 1.6$$

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_{1_i}) 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 $G_9(\overline{XT})$ through $G_{11}(\overline{XT})$ 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 (η_o).

The minimum required equivalent blade section maximum thickness-to-chord ratio ($(t^*/c)_{.75R_{min}}$), 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 $(t^*/c)_{.75R}$.

A final observation on the results concerns the values of the open water efficiency. The "optimum" open water efficiency (η_o) achieved by Triantafyllou is lower than those achieved in variations 1 and 2. A possible reason for this might be the neglect 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

GROUP	ITEM	TRIANTA- FYLLIOU	1	2	3	4
Given	P_E	18153.0	18153.0	18153.0	18153.0	18153.0
	V	24.0	24.0	24.0	24.0	24.0
Design Variable Speci- fied	D	22.0	22.0	22.0		
	A_E/A_O	.85	.85	.85		
	$(t^*/c) .75R$		.0348	.0348		
Design Variables	D				21.9991	21.9659
	P/D	1.1651	1.0036	1.0036	.9981	1.0071
	A_E/A_O				.8205	.8149
	$(t^*/c) .75R$				.0330	.0642
	J	.8286	.7371	.7371	.7343	.7394
Maximize	η_O	.6676	.7091	.7091	.7109	.7066
Restric- tions	D_{lim}		(22.0)	(22.0)	22.0	22.0
	A_E/A_{Omin}		(0.5258)	(0.5258)	.5269	.5267
	$(t^*/c) .75R_{min}$		(0.21266)	(0.50761)	.021998	.053259
Other	N_P	104	116.9	116.9	117.4	116.7
	Q_S	1290000	1080451.	1080451	1064574	1084003
	P_D	25544.0	24051.3	24051.3	24030.3	24094.8

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 $\bar{X}_2$

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:

$$\bar{X} = \left\{ \begin{array}{c} P_E \\ V \\ D \\ P/D \\ A_E/A_O \\ (t^*/c) .75R \end{array} \right\} \quad (8.1)$$

Having specified Q_S and N_P , all of the design variables, as listed in equation (8.1), are not independent. Recalling equations (3.3), (3.11) and (3.13), the following relationship results:

$$P_E = \frac{(1-t_d)}{(1-wt)} \cdot \eta_R \cdot \frac{J K_T}{2\pi K_Q} \cdot \frac{2\pi Q_S}{550} \cdot \frac{N_P}{60} \quad (8.2)$$

Rearranging terms, this equation becomes:

$$\frac{P_E}{V} = \frac{(1-t_d)}{(1-wt)} \cdot \eta_R \cdot \frac{(1-wt)}{n_P D} \cdot \frac{K_T}{K_Q} \cdot \frac{Q_S}{550} \cdot \frac{N_P}{60} \quad (8.3)$$

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:

$$\bar{X} = \begin{pmatrix} V \\ D \\ P/D \\ A_E/A_O \\ (t^*/c)_{.75R} \end{pmatrix} \quad (8.4)$$

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:

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

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:

$$(P_D)_{\text{absorb}} = \frac{2\pi Q_P}{550} \cdot \frac{N_P}{60} \quad (8.6)$$

From equation (3.10), it follows that:

$$(P_D)_{\text{absorb}} = \frac{K_Q \rho n_P^2 D^5}{550} \cdot \frac{2\pi N_P}{60} \quad (8.7)$$

But, equation (3.3) also defines the power delivered to the propeller as:

$$P_D = \frac{2\pi Q_S}{550} \cdot \frac{N_P}{60} \quad (8.8)$$

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

$$P_D \leq (P_D)_{\text{absorb}} \quad (8.9)$$

Rearranging equation (8.9), the constraint $G_{12}(\bar{X}_2)$ follows:

$$G_{12}(\bar{X}_2) = 1 - \frac{(P_D)_{\text{absorb}}}{P_D} \leq 0 \quad (8.10)$$

Further simplification of equation (8.10) gives:

$$G_{12}(\bar{X}_2) = 1 - \frac{Q_P}{Q_S} \leq 0 \quad (8.11)$$

With the design vector $\bar{X}_2$ and $G_{12}(\bar{X}_2)$ defined, the propeller selection problem represented by Design Case No. 2 can be stated under one equation as:

$$\begin{aligned} \text{Minimize: } F(\bar{X}_2) &= \text{OBJ}_{1,2} \\ \text{Subject to: } G_j(\bar{X}_2) &\leq 0 \quad j = 1, \dots, 12 \\ x_{2_i}^{\text{lower}} &\leq x_{2_i} \leq x_{2_i}^{\text{upper}} \quad i = 1, \dots, 5 \end{aligned} \quad (8.12)$$

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) $P_{\text{watvap}} = 0.0206411$ (bars) = .29943921 (psia)
- 3) $P_{\text{atm}} = 1.01312856$ (bars) = 14.6974 (psia)
- 4) $\text{noscrw} = 1$
- 5) $h_{\text{cl}} = 6.7$ (meters) = 21.9827 (ft)
- 6) $z = 6$
- 7) $P_D = 18.9$ (MegaWatts) = 25344.9 (hp)
- 8) $N_p = 110$ (rpm)
- 9) $V_A = 15.65$ (knots)

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

$$\overline{XM} = \begin{pmatrix} J \\ P/D \\ A_E/A_O \end{pmatrix}$$

A restriction for the minimum required expanded area ratio ($(A_E/A_O)_{\text{min}}$), given by equation (4.3), was also considered. This imposed a constraint given by equation (4.4).

Using an iterative scheme [Ref. 4: p. 110] to solve three equations in three unknowns, Markussen maximized the open water efficiency (η_o) to obtain the following results:

$$J = .61095$$

$$P/D = .864380$$

$$A_E/A_O = 36.1861/40.6123 \text{ (m}^2\text{/m}^2\text{)}$$

$$= .891012$$

$$\eta_o = .654391$$

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 $\overline{X_M}$ (NDV = 3) is used in both cases. One variation uses SUBROUTINE STRCNA to evaluate the constraint $G_{12}(\overline{X_M})$ given by equation (4.8). The other uses SUBROUTINE STRCNK to determine $G_{12}(\overline{X_M})$.

The remaining two variations will solve the propeller selection problem using the design vector $\overline{X_2}$ (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) Temp = 64.4 (°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) $n_{scrw} = 1$
- 10) $h_{cl} = 21.9827$ (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 $G_{12}(\overline{X2})$ or $G_{12}(\overline{XM})$ 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 $\overline{XM}$, the following design variables of $\overline{X2}$ become parameters and are specified in the input section of SUBROUTINE ANALIZ (ICALC = 1). The ship's speed (V) is specified as:

$$\begin{aligned}
 V &= V_A / (1 - wt) \\
 &= 15.65 / (1 - .22) \\
 &= 20.0641 \text{ (knots)}
 \end{aligned}$$

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 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:

$$G_j(\overline{XT}) \leq 0 \quad j = 1, \dots, 8, 10, 12$$

Only ten of twelve constraints are considered (NCON = 10). Constraints $G_9(\overline{XM})$ and $G_{11}(\overline{XM})$ 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

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 STRCNK 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 $\overline{X2}$. For constraints, the following are used:

$$G_j(\overline{X2}) \leq 0 \quad j = 1, \dots, 12$$

All twelve constraints are evaluated (NCON = 12).

The upper ($X2_i^{\text{upper}}$) and lower ($X2_i^{\text{lower}}$) limits on the design variables V , P/D , A_E/A_O , $(t^*/c)_{.75R}$, and J are set as:

$$\begin{aligned} 10.0 &\leq V \leq 100.0 \quad (\text{ft/sec}) \\ .4 &\leq P/D \leq 1.4 \\ .4 &\leq A_E/A_O \leq 1.1 \\ .003 &\leq (t^*/c)_{.75R} \leq .50 \\ .01 &\leq J \leq 1.1 \end{aligned}$$

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 ($X2_i$) 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 $\overline{XM}$. Obviously, the values obtained for J and P/D , as well as those for D , and $Rn^*_{.75R}$, are very close to the values generated in Markussen's example. However, the values for A_E/A_O 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 A_E/A_O , as given in Table (I), for $Z = 6$. Markussen's value for A_E/A_O (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 $((t^*/c)_{.75R_{min}})$, 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 (η_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_{cl}) of 21.98 (ft), then, the selected propeller, as defined by $\overline{X2}$, 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

GROUP	ITEM	MARKUSSEN	VARIATIONS			
			1	2	3	4
Given	P_D	25344.9	25344.9	25344.9	25344.9	25344.9
	Q_S	1210130	1210130	1210130	1210130	1210130
	N_P	110	110	110	110	110
Design Variable Specified	V_A	15.65	15.65	15.65		
	V		20.0641	20.0641		
Design Variables	J	.61095	.6475	.6475	.9927	.8753
	V				30.9138	29.5355
	V_A				24.1127	23.0377
	P/D	.864380	.9036	.9036	1.1986	1.0308
	A_E/A_O	.891012	.8018	.8018	.7946	.7986
	$(t^*/c)_{.75R}$		.0397	.0397	.0499	.0638
Maximize	η_O	.654391	.6660	.6660	.7643	.7330
Restrictions	D_{lim}		(30.0)	(30.0)	30.0	30.0
	A_E/A_{Omin}	.574729	.5070	.5070	.4622	.4266
	$(t^*/c)_{.75Rmin}$		(.02729)	(.0647)	.02706	.0638
Other	D	23.53	22.25	22.25	22.36	24.23
	P_E		(14057.3)	(14057.3)	19945.5	20653.7
	$Rn^*_{.75R}$	6.478×10^7	5×10^7	5×10^7	5×10^7	5×10^7

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 $\bar{X}$

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 $\bar{X}$ (see Figure (4.1)) to:

$$\bar{X} = \begin{pmatrix} D \\ P/D \\ A_E/A_O \\ (t^*/c) .75R \end{pmatrix} \quad (9.1)$$

For this study, the design vector $\bar{X}$ 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:

$$\overline{X3} = \left\{ \begin{array}{l} P/D \\ A_E/A_O \\ (t^*/c) .75R \end{array} \right\} \quad (9.2)$$

2. Powering Constraint(s)

Having determined the design vector $\overline{X3}$, a final restriction to the general propeller selection problem, as stated by equation (4.24), remains for consideration. This restriction constitutes the remaining constraint $G_{12}(\overline{X})$ mentioned in Chapter IV as well as an additional constraint.

In the "matching" problem, the selected propeller, as defined by $\overline{X3}$, 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:

$$P_E \leq (P_E)_{dev} \quad (9.3)$$

The constraint $G_{12}(\overline{X3})$ follows accordingly as:

$$G_{12}(\overline{X3}) = 1 - \frac{(P_E)_{dev}}{P_E} \leq 0 \quad (9.4)$$

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:

$$(P_D)_{\text{absorb}} \leq P_D \quad (9.5)$$

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

$$G_9(\bar{X3}) = \frac{(P_D)_{\text{absorb}}}{P_D} - 1 \leq 0 \quad (9.6)$$

Further simplification of equation (9.6) gives:

$$G_9(\bar{X3}) = \frac{Q_P}{Q_S} - 1 \leq 0 \quad (9.7)$$

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 $\overline{X3}$ and the constraints $G_{12}(\overline{X3})$ and $G_9(\overline{X3})$ defined, the propeller selection problem represented by Design Case No. 3 can now be stated under one equation as:

$$\begin{aligned} \text{Minimize:} \quad & F(\overline{X3}) = \text{OBJ}_j \\ \text{Subject to:} \quad & G_j(\overline{X3}) \leq 0 \quad j = 1, \dots, 12 \quad (9.8) \\ & x3_i^{\text{lower}} \leq x_i \leq x3_i^{\text{upper}} \quad i = 1, \dots, 3 \end{aligned}$$

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) $N = 105\text{--}110$ (rpm)
- 4) $D_{\text{lim}} = 23$ (ft)
- 5) $h_{cl} = 19$ (ft)

The variation of ship speed (V) and of hull effective power (P_E), thrust deduction factor (td) and the wake fraction (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) Temp = 59 ($^{\circ}$ F)
- 2) $\rho = 1.9905$ (lbf-sec²/ft⁴)
- 3) $p_{\text{watvap}} = .247$ (psia)
- 4) wt = .22
- 5) td = .1725
- 6) noscrw = 1
- 7) $h_{cl} = 19.0$ (ft)
- 8) Z = 6
- 9) promat = 5 (stainless teel, 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 (η_o) and designed a propeller with the following characteristics:

- 1) J = .852
- 2) $K_T = .242$

- 3) $K_Q = .0478$
- 4) $\eta_o = .691$
- 5) $A_E/A_O = .767$
- 6) $bldwt = 7617.2 \text{ (lbf)}$

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, $(t^*/c)_{.75R}$ is approximately .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) $Temp = 59 \text{ (}^\circ F)$
- 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) $p_{\text{atm}} = 14.7$ (psia)
- 6) $wt = .22$
- 7) $\eta_R = 1.025$
- 8) $\text{noscw} = 1$
- 9) $h_{cl} = 19.0$ (ft)
- 10) $Z = 6$
- 11) $\text{promat} = 5$ (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 $G_9(\overline{X3})$ and $G_{12}(\overline{X3})$ 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 WGTAL has been added.

1. Programming Details

All twelve constraints are evaluated ($NCON = 12$). The upper ($X3_i^{upper}$) and lower ($X3_i^{lower}$) limits on the design variables P/D , A_E/A_O and $(t^*/c)_{.75R}$ are set to be:

$$.4 \leq P/D \leq 1.4$$

$$.4 \leq A_E/A_O \leq 1.1$$

$$.003 \leq (t^*/c)_{.75R} \leq .50$$

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 ($X3_i$) 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 η_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

GROUP	ITEM	VASSILOPOULOS	PROBLEM	
			1	2
Given	P_E	21292.6	21292.6	17630.0
	V	24.24	24.24	23.0
	Q_S	1500607	1500607	1500607
	N_P	105	105	105
Design Variable Specified	D	22.0	22.0	22.0
Design Variables	P/D	*	1.1813	1.0906
	A_E/A_O	.767	.7944	.7742
	$(t^*/c) .75R$	.040	.0794	.0681
Minimize	bldwt	—	12842.6	10464.7
Maximize	η_O	.691	—	—
Restrictions	D_{lim}	—	—	—
	A_E/A_{Omin}	—	.8515	.7722
	$(t^*/c) .75R_{min}$	—	.0691	.0681
Other	J	.852	.8290	.7866
	K_T	.242	.2349	.2063
	K_Q	.0478	.0448	.0372
	η_O	—	.6915	.6950
	bldwt	7617.2	—	—

* P/D varies with R

X. 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

FORTTRAN VARIABLE CROSS REFERENCE LIST

<u>Symbol</u>	<u>Fortran Variable</u>
A_E/A_O	AEDVAO
$(A_E/A_O)_{min}$	AEAOMN
bldwt	WEIGHT
$C_{.75R}$	C75R
D	DIA
D_{lim}	DIALIM
h_{cl}	HCL
J	_RJ
K_Q	KQ
K_T	KT
noscrw	NOSCRW
N_P	N
P_E	PE
P_D	PD
P/D	PDIVD
P_{watvap}	PWATVA
P_{atm}	PATM
promat	PROMAT
Q_S	QS
$Rn^*_{.75R}$	R75R
S_C	SC
td	TD

APPENDIX A (CONT.)

<u>Symbol</u>	<u>Fortran Variable</u>
Temp	TEMP
$(t^*/c)_{.75R}$	TC75R
V (ft/sec)	V
V (knots)	VK
wt	WT
z	Z
η_o	ETAO
η_R	ETARR
v	WATNU
ρ	WATRO

APPENDIX B

SUBROUTINE LISTINGS

SUBROUTINE ELDPRP				APPOC0010
				APPOC0020
				APPOC0030
SUBROUTINE: BLCPRP				APPOC0040
INPUT				APPOC0050
				APPOC0060
AECVAO				APPOC0070
DIA				APPOC0080
Z				APPOC0090
COMMON /THICD/				APPOC0100
				APPOC0110
				APPOC0120
				APPOC0130
				APPOC0140
				APPOC0150
				APPOC0160
				APPOC0170
				APPOC0180
				APPOC0190
				APPOC0200
				APPOC0210
				APPOC0220
				APPOC0230
				APPOC0240
				APPOC0250
				APPOC0260
				APPOC0270
				APPOC0280
				APPOC0290
				APPOC0300
				APPOC0310
				APPOC0320
				APPOC0330
				APPOC0340
				APPOC0350
				APPOC0360
				APPOC0370
				APPOC0380
				APPOC0390
				APPOC0400
				APPOC0410
				APPOC0420
				APPOC0430
				APPOC0440
				APPOC0450
				APPOC0460
				APPOC0470
				APPOC0480

DATE OF LAST REVISION: APR 83	DEFINITION
	EXPANDED AREA RATIO
	PROPELLER DIAMETER (FEET)
	NO. OF PROPELLER BLADES
	BLADE SECTION MAXIMUM
	THICKNESS ALONG PROPELLER
	RADIUS (FEET)
	BLADE SECTION AREAS (FEET**2)
	LOCATION OF BLADE CROSS-SEC-
	TIONAL AREA CENTROID WITH
	RESPECT TO GENERATOR LINE
	(FEET)
	LOCATION OF BLADE CROSS-SEC-
	TIONAL AREA CENTROID WITH
	RESPECT TO PITCH-REFERENCE
	LINE (FEET)
	BLADE SECTION CHORD LENGTHS
	(FEET)
	ORIGINATE OF CRITICAL POINT NO.
	1 ON BLADE SECTION PERIPHERY
	WITH RESPECT TO A SYSTEM OF
	AXES PARALLEL AND NORMAL TO
	PITCH-REFERENCE LINE WITH ORI-
	GIN AT THE CENTROID OF THE
	SECTION (FEET)
	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 ORI-
	GIN AT THE CENTROID OF THE
	SECTION (FEET)
	ORIGINATE OF CRITICAL POINT NO.
	2 ON BLADE SECTION PERIPHERY
	WITH RESPECT TO A SYSTEM OF
	AXES PARALLEL AND NORMAL TO
	PITCH-REFERENCE LINE WITH ORI-
	GIN AT THE CENTROID OF THE
	SECTION (FEET)
	ABSCISSA OF CRITICAL POINT NO.
	2 ON BLADE SECTION PERIPHERY
	WITH RESPECT TO A SYSTEM OF

COMMON/AREBLD/	COMMON/CGY/	COMMON/CRDLNT/	COMMON/VALW1/	COMMON/VALW1/	COMMON/VALU2/	COMMON/VALW2/
COMMON/CGX/		COMMON/VALU1/				

CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC


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5 REAL*4 FJ,C75R,R75R,KI,KQ
1 TQOR,T1XR,T2OR,T3OR,T4OR,T5OR,T6OR,T7OR,T75R,T8OR,T9OR,
1 REAL*4 CR(10),AR(10),BR(10),PLF(10),PLA(10),TR(10),VIF(10,11),
1 V2F(10,11),V1A(10,10),V2A(10,10),VFAC(11),YBACK(11),
2 PA(10),Y(11),DELPA(10),DLPSM,XA(10),YA(10),SUMAA,
3 SUMAXA,SUMAYA,SMAX2A,SMAY2A,FF(11),DELPF(11),AF(11),DLPF,
4 XF(11),YFC(11),SUMAF,SUMAXF,SMAYF,SMAY2F,AREAL(10),
5 XH(10),YPR(10),R1XNA(10),R1YNA(10),XCG(10),YCG(10),
1 REAL*4 U1(10),U2(10),U3(10),U4(10),W1(10),W2(10),W3(10),W4(10),
1 YBK,YFC,DN
1 INTEGER*4 I,IR,IPI
COMMON /GLOECM/ETAQ,WEIGHT,AEDVAO,DIA,N,PE,FUVD,QS,TC75R,V,KJCNL,
1RJCNV,R75RCL,R75RCU,AEAOL,AEAOCU,TC75CL,TC75CU,PDMBAL,DIACNU,
2AEACCV,TCSTFS,RJ
COMMON /PAR4M/VK,TD,WI,Z,WATKO,WATNU,TEMP,NCSCRW,HCL,PATM,PWATVA,
1PRQHAT,LIALIM,ETARR,AEAOMN,TC75MH,SC
COMMON /THICD/TCOR,T1XR,T2OR,T3OR,T4OR,T5OR,T6OR,T7OR,T75R,T8OR,
1T9OR,T1CCR,RAT
COMMON /AREELD/AREA
COMMON /CGX/XCG
COMMON /CGY/YCG
COMMON /CROINT/CR
COMMON /VAL1/U1
COMMON /VAL2/U2
COMMON /VAL3/U3
COMMON /VAL4/U4
COMMON /VAL1/W1
COMMON /VAL2/W2
COMMON /VAL3/W3
COMMON /VAL4/W4
COMMON /A2MCMX/R1YNA
COMMON /A2MCMY/R1XNA
DETERMINE CFORD LENGTHS ALONG BLADE RADIUS USING TABLE (1), REF 2
IF(1.NOT.(2.EQ.3.0))GO TC 1
CR(1)=(1.5532*AEDVAO*DIA)/Z
GO TO 5
1 CONTINUE
IF(1.NOT.(2.EQ.4.0))GO TO 2
CR(1)=(1.5694*AEDVAO*DIA)/Z
GO TO 5
2 CONTINUE
IF(1.NOT.(2.EQ.5.0))GO TC 3
CR(1)=(1.5894*AEDVAO*DIA)/Z
GO TO 5
3 CONTINUE

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CC

```

IF (.NOT. (Z.EQ.6.0) ) GO TC 4
CR(1) = (1.5854 * AEDVAU * DIA) / Z
GO TO 5
4 CONTINUE
CR(1) = (1.6180 * AEDVAU * DIA) / Z
5 CONTINUE
IF (.NOT. (Z.EQ.3.0) ) GO TC 6
CR(2) = (1.6330 * AEDVAU * DIA) / Z
CR(3) = (1.8320 * AEDVAU * DIA) / Z
CR(4) = (2.0000 * AEDVAU * DIA) / Z
CR(5) = (2.1200 * AEDVAU * DIA) / Z
CR(6) = (2.1860 * AEDVAU * DIA) / Z
CR(7) = (2.1680 * AEDVAU * DIA) / Z
CR(8) = (2.1270 * AEDVAU * DIA) / Z
CR(9) = (1.6570 * AEDVAU * DIA) / Z
CR(10) = (0.0000 * AEDVAU * DIA) / Z
GO TO 7
6 CONTINUE
CR(2) = (1.6620 * AEDVAU * DIA) / Z
CR(3) = (1.8820 * AEDVAU * DIA) / Z
CR(4) = (2.0500 * AEDVAU * DIA) / Z
CR(5) = (2.1520 * AEDVAU * DIA) / Z
CR(6) = (2.1870 * AEDVAU * DIA) / Z
CR(7) = (2.1440 * AEDVAU * DIA) / Z
CR(8) = (1.9700 * AEDVAU * DIA) / Z
CR(9) = (1.5820 * AEDVAU * DIA) / Z
CR(10) = (0.0000 * AEDVAU * DIA) / Z
7 CONTINUE
CALCULATE POSITION OF GENERATOR LINE (I.E., AR(1)) AND POSITION OF
MAXIMUM ELASE SECTION THICKNESS (I.E., ER(1)) USING FIGURE (1) AND
TABLE (1), REF 2
IF (.NOT. (Z.EQ.3.0) ) GO TC 8
AR(1) = (.617 * CR(1))
BR(1) = (.350 * CR(1))
GO TO 12
8 CONTINUE
IF (.NOT. (Z.EQ.4.0) ) GO TC 9
AR(1) = (.61832 * CR(1))
BR(1) = (.350 * CR(1))
GO TO 12
9 CONTINUE
IF (.NOT. (Z.EQ.5.0) ) GO TC 10
AR(1) = (.61832 * CR(1))
BR(1) = (.350 * CR(1))
GO TO 12
10 CONTINUE

```

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APP01450
APP01460
APP01470
APP01480
APP01490
APP01500
APP01510
APP01520
APP01530
APP01540
APP01550
APP01560
APP01570
APP01580
APP01590
APP01600
APP01610
APP01620
APP01630
APP01640
APP01650
APP01660
APP01670
APP01680
APP01690
APP01700
APP01710
APP01720
APP01730
APP01740
APP01750
APP01760
APP01770
APP01780
APP01790
APP01800
APP01810
APP01820
APP01830
APP01840
APP01850
APP01860
APP01870
APP01880
APP01890
APP01900
APP01910
APP01920

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CC
CC
CC

APP01530
 APP01540
 APP01550
 APP01560
 APP01570
 APP01580
 APP01590
 APP02000
 APP02010
 APP02020
 APP02030
 APP02040
 APP02050
 APP02060
 APP02070
 APP02080
 APP02090
 APP02100
 APP02110
 APP02120
 APP02130
 APP02140
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 APP02280
 APP02290
 APP02300
 APP02310
 APP02320
 APP02330
 APP02340
 APP02350
 APP02360
 APP02370
 APP02380
 APP02390
 APP02400

IF (.NOT. (Z.EQ.6.0) .AND. TC 11
 AR(1)=C.61832*CR(1)
 BR(1)=C.350*CR(1)
 GO TO 12
 11 CONTINUE
 AR(1)=C.6178*CR(1)
 BR(1)=C.350*CR(1)
 12 CONTINUE
 IF (.NOT. (Z.EQ.3.0) .AND. TC 13
 AR(2)=C.612*CR(2)
 AR(3)=C.611*CR(3)
 AR(4)=C.595*CR(4)
 AR(5)=C.583*CR(5)
 AR(6)=C.558*CR(6)
 AR(7)=C.526*CR(7)
 AR(8)=C.481*CR(8)
 AR(9)=C.400*CR(9)
 AR(10)=0.0
 BR(2)=C.350*CR(2)
 BR(3)=C.350*CR(3)
 BR(4)=C.350*CR(4)
 BR(5)=C.355*CR(5)
 BR(6)=C.385*CR(6)
 BR(7)=C.442*CR(7)
 BR(8)=C.476*CR(8)
 BR(9)=C.500*CR(9)
 BR(10)=0.0
 GO TO 14
 13 CONTINUE
 AR(2)=C.617*CR(2)
 AR(3)=C.613*CR(3)
 AR(4)=C.591*CR(4)
 AR(5)=C.586*CR(5)
 AR(6)=C.561*CR(6)
 AR(7)=C.524*CR(7)
 AR(8)=C.463*CR(8)
 AR(9)=C.351*CR(9)
 AR(10)=0.0
 BR(2)=C.350*CR(2)
 BR(3)=C.350*CR(3)
 BR(4)=C.351*CR(4)
 BR(5)=C.355*CR(5)
 BR(6)=C.385*CR(6)
 BR(7)=C.443*CR(7)
 BR(8)=C.479*CR(8)
 BR(9)=C.500*CR(9)
 BR(10)=0.0
 GO TO 14
 14 CONTINUE

```

CCCCCCC
      DETERMINE "FORWARD" (P=0 TO 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=1,10
        PLF(I)=BR(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)=T10CR
      INITIALIZE VALUES FOR "V1" & "V2" (P=0 TO P=+1) AND "V1" & "V2"
      (P=0 TO P=-1) IN RELATIONS (2) AND (3), REF 2, USING VALUES FROM
      TABLE (2), REF 2
      ... BEGIN AT R=.18K FOR PROPELLERS WITH 3 OR 7 BLADES
      IF (.NOT. (Z.EQ.3.0)).OR.(Z.EQ.7.0)) GO TO 16
      V1F(1,1)=0.0000
      V1F(1,2)=0.0063
      V1F(1,3)=0.0336
      V1F(1,4)=0.0558
      V1F(1,5)=0.0851
      V1F(1,6)=0.1238
      V1F(1,7)=0.1761
      V1F(1,8)=0.2052
      V1F(1,9)=0.2496
      V1F(1,10)=0.2947
      V1F(1,11)=0.3678
      V1A(1,1)=0.0000
      V1A(1,2)=0.0232
      V1A(1,3)=0.0722
      V1A(1,4)=0.1028
      V1A(1,5)=0.1352
      APP0241U
      APP0242U
      APP0243U
      APP0244U
      APP0245U
      APP0246U
      APP0247U
      APP0248U
      APP0249U
      APP0250U
      APP0251U
      APP0252U
      APP0253U
      APP0254U
      APP0255U
      APP0256U
      APP0257U
      APP0258U
      APP0259U
      APP0260U
      APP0261U
      APP0262U
      APP0263U
      APP0264U
      APP0265U
      APP0266U
      APP0267U
      APP0268U
      APP0269U
      APP0270U
      APP0271U
      APP0272U
      APP0273U
      APP0274U
      APP0275U
      APP0276U
      APP0277U
      APP0278U
      APP0279U
      APP0280U
      APP0281U
      APP0282U
      APP0283U
      APP0284U
      APP0285U
      APP0286U
      APP0287U
      APP0288U

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151


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V1A(2,5)=0.4630
V1A(2,1)=0.2826
V2F(2,1)=1.0000
V2F(2,2)=0.5750
V2F(2,3)=0.3875
V2F(2,4)=0.1770
V2F(2,5)=0.1190
V2F(2,6)=0.4777
V2F(2,7)=0.3905
V2F(2,8)=0.3840
V2F(2,9)=0.1560
V2F(2,10)=0.0000
V2A(2,1)=1.0000
V2A(2,2)=0.5446
V2A(2,3)=0.5847
V2A(2,4)=0.5995
V2A(2,5)=0.5845
V2A(2,6)=0.5535
V2A(2,7)=0.5060
V2A(2,8)=0.1455
V2A(2,9)=0.6400
V2A(2,10)=0.0000
..... CONTINUE FOR R=.3R
V1F(3,1)=0.0000
V1F(3,2)=0.0278
V1F(3,3)=0.1488
V1F(3,4)=0.3300
V1F(3,5)=0.5033
V1F(3,6)=0.7099
V1F(3,7)=0.1191
V1F(3,8)=0.1445
V1F(3,9)=0.1760
V1F(3,10)=0.2186
V1A(3,1)=0.2923
V1A(3,2)=0.0000
V1A(3,3)=0.0033
V1A(3,4)=0.0202
V1A(3,5)=0.0376
V1A(3,6)=0.0943
V1A(3,7)=0.1330
V1A(3,8)=0.1790
V1A(3,9)=0.2040
V2F(3,1)=1.0000
V2F(3,2)=0.2300

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APPJ4810
 APPJ4820
 APPJ4830
 APPJ4840
 APPJ4850
 APPJ4860
 APPJ4870
 APPJ4880
 APPJ4890
 APPJ4900
 APPJ4910
 APPJ4920
 APPJ4930
 APPJ4940
 APPJ4950
 APPJ4960
 APPJ4970
 APPJ4980
 APPJ4990
 APPJ5000
 APPJ5010
 APPJ5020
 APPJ5030
 APPJ5040
 APPJ5050
 APPJ5060
 APPJ5070
 APPJ5080
 APPJ5090
 APPJ5100
 APPJ5110
 APPJ5120
 APPJ5130
 APPJ5140
 APPJ5150
 APPJ5160
 APPJ5170
 APPJ5180
 APPJ5190
 APPJ5200
 APPJ5210
 APPJ5220
 APPJ5230
 APPJ5240
 APPJ5250
 APPJ5260
 APPJ5270
 APPJ5280

V2F(4,5)=C.1593
 V2F(4,6)=C.1590
 V2F(4,7)=C.1522
 V2F(4,8)=C.1535
 V2F(4,9)=C.1235
 V2F(4,10)=C.1193
 V2A(4,1)=C.0000
 V2A(4,2)=C.0000
 V2A(4,3)=C.0000
 V2A(4,4)=C.0000
 V2A(4,5)=C.0000
 V2A(4,6)=C.0000
 V2A(4,7)=C.0000
 V2A(4,8)=C.0000
 V2A(4,9)=C.0000
 V2A(4,10)=C.0000

... CONTINUE FOR R=.5R

V1F(5,1)=C.0000
 V1F(5,2)=C.0000
 V1F(5,3)=C.0000
 V1F(5,4)=C.0000
 V1F(5,5)=C.0000
 V1F(5,6)=C.0000
 V1F(5,7)=C.0000
 V1F(5,8)=C.0000
 V1F(5,9)=C.0000
 V1F(5,10)=C.0000
 V1A(5,1)=C.0000
 V1A(5,2)=C.0000
 V1A(5,3)=C.0000
 V1A(5,4)=C.0000
 V1A(5,5)=C.0000
 V1A(5,6)=C.0000
 V1A(5,7)=C.0000
 V1A(5,8)=C.0000
 V1A(5,9)=C.0000
 V1A(5,10)=C.0000
 V2F(5,1)=C.0000
 V2F(5,2)=C.0000
 V2F(5,3)=C.0000
 V2F(5,4)=C.0000
 V2F(5,5)=C.0000
 V2F(5,6)=C.0000
 V2F(5,7)=C.0000
 V2F(5,8)=C.0000
 V2F(5,9)=C.0000
 V2F(5,10)=C.0000

CC


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V2A(7,3)=C.5400
V2A(7,4)=C.1500
V2A(7,5)=C.6400
V2A(7,6)=C.100
V2A(7,7)=C.3600
V2A(7,8)=C.1900
V2A(7,9)=C.575
V2A(7,10)=C.0000
... CCATINUE FOR K=.8R
V1F(8,1)=0.0000
V1F(8,2)=0.0000
V1F(8,3)=0.0000
V1F(8,4)=0.0000
V1F(8,5)=0.0000
V1F(8,6)=0.0000
V1F(8,7)=0.0000
V1F(8,8)=0.0000
V1F(8,9)=0.0000
V1F(8,10)=0.0000
V1A(8,1)=0.0000
V1A(8,2)=0.0000
V1A(8,3)=0.0000
V1A(8,4)=0.0000
V1A(8,5)=0.0000
V1A(8,6)=0.0000
V1A(8,7)=0.0000
V1A(8,8)=0.0000
V1A(8,9)=0.0000
V1A(8,10)=0.0000
V2F(8,1)=1.0000
V2F(8,2)=0.5635
V2F(8,3)=0.5205
V2F(8,4)=0.7635
V2F(8,5)=0.5265
V2F(8,6)=0.5765
V2F(8,7)=0.5925
V2F(8,8)=0.5025
V2F(8,9)=0.1050
V2F(8,10)=0.0000
V2A(8,1)=1.0000
V2A(8,2)=0.5600
V2A(8,3)=0.5400
V2A(8,4)=0.7500
V2A(8,5)=0.5400

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CCC

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APP06250
APP06260
APP06270
APP06280
APP06290
APP06300
APP06310
APP06320
APP06330
APP06340
APP06350
APP06360
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APP06380
APP06390
APP06400
APP06410
APP06420
APP06430
APP06440
APP06450
APP06460
APP06470
APP06480
APP06490
APP06500
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APP06540
APP06550
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APP06570
APP06580
APP06590
APP06600
APP06610
APP06620
APP06630
APP06640
APP06650
APP06660
APP06670
APP06680
APP06690
APP06700
APP06710
APP06720

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V2A(8:6)=C:£100
V2A(8:7)=C:£600
V2A(8:8)=C:£1900
V2A(8:9)=C:£575
V2A(8:10)=0.0000
... CONTINUE FOR R=.9R
V1F(9:1)=0.000
V1F(9:2)=0.000
V1F(9:3)=0.000
V1F(9:4)=0.000
V1F(9:5)=0.000
V1F(9:6)=0.000
V1F(9:7)=0.000
V1F(9:8)=0.000
V1F(9:9)=0.000
V1F(9:10)=0.000
V1A(9:1)=0.000
V1A(9:2)=0.000
V1A(9:3)=0.000
V1A(9:4)=0.000
V1A(9:5)=0.000
V1A(9:6)=0.000
V1A(9:7)=0.000
V1A(9:8)=0.000
V1A(9:9)=0.000
V1A(9:10)=0.000
V2F(9:1)=1.000
V2F(9:2)=0.000
V2F(9:3)=0.000
V2F(9:4)=0.000
V2F(9:5)=0.000
V2F(9:6)=0.000
V2F(9:7)=0.000
V2F(9:8)=0.000
V2F(9:9)=0.000
V2F(9:10)=0.000
V2A(9:1)=1.000
V2A(9:2)=0.000
V2A(9:3)=0.000
V2A(9:4)=0.000
V2A(9:5)=0.000
V2A(9:6)=0.000
V2A(9:7)=0.000
V2A(9:8)=0.000
V2A(9:9)=0.000
V2A(9:10)=0.000

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CCC

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APPU6730
APPU6740
APPU6750
APPU6760
APPU6770
APPU6780
APPU6790
APPU6800
APPU6810
APPU6820
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APPU6840
APPU6850
APPU6860
APPU6870
APPU6880
APPU6890
APPU6900
APPU6910
APPU6920
APPU6930
APPU6940
APPU6950
APPU6960
APPU6970
APPU6980
APPU6990
APPU7000
APPU7010
APPU7020
APPU7030
APPU7040
APPU7050
APPU7060
APPU7070
APPU7080
APPU7090
APPU7100
APPU7110
APPU7120
APPU7130
APPU7140
APPU7150
APPU7160
APPU7170
APPU7180
APPU7190
APPU7200

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APP07210
APP07220
APP07230
APP07240
APP07250
APP07260
APP07270
APP07280
APP07290
APP07300
APP07310
APP07320
APP07330
APP07340
APP07350
APP07360
APP07370
APP07380
APP07390
APP07400
APP07410
APP07420
APP07430
APP07440
APP07450
APP07460
APP07470
APP07480
APP07490
APP07500
APP07510
APP07520
APP07530
APP07540
APP07550
APP07560
APP07570
APP07580
APP07590
APP07600
APP07610
APP07620
APP07630
APP07640
APP07650
APP07660
APP07670
APP07680

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V2A(9,5)=0.0975
V2A(9,10)=0.0000
... CONTINUE FOR R=1,OR
V1F(10,1)=0.0000
V1F(10,2)=0.0000
V1F(10,3)=0.0000
V1F(10,4)=0.0000
V1F(10,5)=0.0000
V1F(10,6)=0.0000
V1F(10,7)=0.0000
V1F(10,8)=0.0000
V1F(10,9)=0.0000
V1F(10,10)=0.0000
V1A(10,1)=0.0000
V1A(10,2)=0.0000
V1A(10,3)=0.0000
V1A(10,4)=0.0000
V1A(10,5)=0.0000
V1A(10,6)=0.0000
V1A(10,7)=0.0000
V1A(10,8)=0.0000
V1A(10,9)=0.0000
V1A(10,10)=0.0000
V2F(10,1)=0.0000
V2F(10,2)=0.0000
V2F(10,3)=0.0000
V2F(10,4)=0.0000
V2F(10,5)=0.0000
V2F(10,6)=0.0000
V2F(10,7)=0.0000
V2F(10,8)=0.0000
V2F(10,9)=0.0000
V2F(10,10)=0.0000
V2A(10,1)=0.0000
V2A(10,2)=0.0000
V2A(10,3)=0.0000
V2A(10,4)=0.0000
V2A(10,5)=0.0000
V2A(10,6)=0.0000
V2A(10,7)=0.0000
V2A(10,8)=0.0000
V2A(10,9)=0.0000
V2A(10,10)=0.0000

```

CC

C


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18 CC
19 CC
20 CC
21 CC
22 CC
23 CC
24 CC

CONTINUE
IF(.NCT.((1.EQ.8).OR.(1.EQ.9)))GO TO 19
DELPA(1)=(PLA(IR)/10.0)*C.5
GC TO 20
CONTINUE
DELPA(1)=(PLA(IR)/10.0)*1.0
CONTINUE
AA(1)=(0.5*(HA(IP1)+HA(1)))*DELPA(1)
DLPASM=DLPASM+DELPA(1)
XA(1)=(DLPASM-DELPA(1))/2.0
YA(1)=(Y(IP1)+Y(1))/2.0
SLMAA=SUMAA+AA(1)
SLMAXA=SUMAXA+(AA(1)*XA(1))
SLMAYA=SUMAYA+(AA(1)*YA(1))
SPAX2A=SMAX2A+(AA(1)*((XA(1))**2)+(YA(1))**2))
SPAY2A=SMAY2A+(AA(1)*((YA(1))**2)+(XA(1))**2))
((1.0/12.0)*(DELPA(1))*((HA(1)+HA(IP1))/2.0)**3))
CONTINUE
1
21
CC
CC
CC
CC

:CONTINUE WITH "FORWARD" PORTION (P=0 TO P=+1) OF BLADE
SECTION AS DEPICTED IN FIGURE (1), REF 2
DC 25 J=1,10
IF1=1+1
YFACE(1)=(V1F(IR,1))*TR(IR)-(U.1*TR(IR))
YEACK(1)=(V1F(IR,1))+V2F(IR,1)*TR(IR)-(0.1*TR(IR))
HF(1)=YBACK(1)-YFACE(1)/2.0
Y(1)=(YBACK(1)+YFACE(1))*TR(IR)-(0.1*TR(IR))
YEACK(IP1)=(V1F(IR,IP1)+V2F(IR,IP1))*TR(IR)
HF(IP1)=YBACK(IP1)-YFACE(IP1)/2.0
Y(IP1)=(YBACK(IP1)+YFACE(IP1))/2.0
IF(.NCT.((1.EQ.1).OR.(1.EQ.2)))GO TO 22
DELPA(1)=(PLF(IR)/10.0)*2.0
GC TO 24
CONTINUE
IF(.NCT.((1.EQ.7).OR.(1.EQ.8).OR.(1.EQ.9).OR.(1.EQ.10)))
GC TO 23
DELPA(1)=(PLF(IR)/10.0)*0.5
GC TO 24
CONTINUE
DELPA(1)=(PLF(IR)/10.0)*1.0
CONTINUE
AF(1)=(0.5*(HF(IP1)+HF(1)))*DELPA(1)
DLPASM=DLPASM+DELPA(1)
APP0E170
APP0E180
APP0E190
APP0E200
APP0E210
APP0E220
APP0E230
APP0E240
APP0E250
APP0E260
APP0E270
APP0E280
APP0E290
APP0E300
APP0E310
APP0E320
APP0E330
APP0E340
APP0E350
APP0E360
APP0E370
APP0E380
APP0E390
APP0E400
APP0E410
APP0E420
APP0E430
APP0E440
APP0E450
APP0E460
APP0E470
APP0E480
APP0E490
APP0E500
APP0E510
APP0E520
APP0E530
APP0E540
APP0E550
APP0E560
APP0E570
APP0E580
APP0E590
APP0E600
APP0E610
APP0E620
APP0E630
APP0E640

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IF(.NOT.(UN.LT.AK(IR)))GO TO 31
XCG(IR)=AR(IR)-DN
GC TC 33
CCNTINCE
IF(.NOT.(DN.GT.AR(IR)))GO TO 32
XCG(IR)=-((DN-AR(IR))
GC TO 33
CCNTINLE
XCG(IR)=G.O
CCNTINLE
YCG(IR)=YPRL(IR)
DETERMINE "CRITICAL PCINTS" OF A BLADE SECTION WITH RESPECT
TO NEUTRAL AXES WHERE STRESSES ARE LIKELY TO BE A MAXIMUM
** CALCULATE CRDINATE (U2) AND ABCISSA (W2) OF CRITICAL POINT
NG. 2 DEPICTED IN FIGURE (10), REF 8
W2(IR)=(AK(IR)-BR(IR))-XCG(IR)
U2(IR)=(((VIA(IR,1)+V2A(IR,1))*((TR(IR)-(O.1*TR(IR)))))+(
(O.1*TR(IR)))-YPRL(IR)
** CALCULATE ORDINATE (U4) AND ABCISSA (W4) OF CRITICAL POINT
NE. 4 DEPICTED IN FIGURE (10), REF 8
W4(IR)=W2(IR)
U4(IR)=(((VIA(IR,1))*((TR(IR)-(O.1*TR(IR))))-YPRL(IR)
** CALCULATE ORDINATE (U1) AND ABCISSA (W1) OF CRITICAL POINT
NG. 1 DEPICTED IN FIGURE (10), REF 8
W1(IR)=-(((CR(IR)-AK(IR))+XCG(IR))
YBK=((VIA(IR,10)+V2A(IR,10))*((TR(IR)-(O.1*TR(IR))))
YFC=((VIA(IR,10))*((TR(IR)-(O.1*TR(IR))))
IF(.NOT.(YCG(IR).GT.YBK))GC TC 40
U1(IR)=YFC-YCG(IR)
GC TC 45
CCNTINLE
IF(.NOT.(YCG(IR).LE.YBK)).AND.(YCG(IR).GE.YFC)))GO TO 44
IF(.NOT.(YFC.NGT.((ABS(YCG(IR)-YFC)).GT.(ABS(YBK-YCG(IR))))))
GC TO 41
U1(IR)=YFC-YC6(IR)
GC TO 43
CCNTINUE
IF(.NOT.(YFC.NGT.((ABS(YCG(IR)-YFC)).LT.(ABS(YBK-YCG(IR))))))
GC TO 42
U1(IR)=YBK-YCG(IR)
GC TC 43

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```

42      CCNT INUE
43      U1( IR)=0.0
44      CCNT INUE
45      GC TO 45
      CCNT INUE
      U1( IR)=YBK-YCG( IR)
      CCNT INUE
      * CALCULATE ORDINATE (U3) AND ABSCISSA (W3) OF CRITICAL POINT
      NC. 3 DEPICTED IN FIGURE (10), REF 8
      W3( IR)=CR( IR)-ABS(W1( IR))
      YBK=(V1F( IR,11)+V2F( IR,11))*TR( IR)-(0.1*TR( IR))
      YFC=(V1F( IR,11))*TR( IR)-(0.1*TR( IR))
      IF (.NOT. (YCG( IR).GT.YBK)) GC TC 46
      U3( IR)=YFC-YCG( IR)
      GC TC 46
      CCNT INUE
      IF (.NOT. ((YCG( IR).LE.YBK).AND.(YCG( IR).GE.YFC))) GO TO 50
      IF (.NOT. ((ABS(YCG( IR)-YFC)).GT.(AES(YBK-YCG( IR))))))
      GC TO 47
      U3( IR)=YFC-YCG( IR)
      GC TO 49
      CCNT INUE
      IF (.NOT. ((ABS(YCG( IR)-YFC)).LT.(AES(YBK-YCG( IR))))))
      GC TO 48
      U3( IR)=YBK-YCG( IR)
      GC TC 49
      CCNT INUE
      U3( IR)=0.0
      CCNT INUE
      GC TO 51
      CCNT INUE
      U3( IR)=YBK-YCG( IR)
      CCNT INUE
      RETURN
      END

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APP05610
APP05620
APP05630
APP05640
APP05650
APP05660
APP05670
APP05680
APP05690
APP05700
APP05710
APP05720
APP05730
APP05740
APP05750
APP05760
APP05770
APP05780
APP05790
APP05800
APP05810
APP05820
APP05830
APP05840
APP05850
APP05860
APP05870
APP05880
APP05890
APP05900
APP05910
APP05920
APP05930
APP05940
APP05950
APP05960
APP05970
APP05980

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SUBROUTINE ELDVCL(VCLBLD)
SUBROUTINE: BLEVOL
INPUT      OUTPUT
DIA
COMMON/AREBLD/      VOLBLD
REAL*4     EIAO,WEIGHT,AEDVAO,DIA,N,PE,PDIVC,QS,TC75R,V,
1          FJCNL,RJCNV,R75RCL,R75RCU,AEACCU,TC75CL,TC75CU,
2          PCWBL,DIAACNU,AEACCV,TCSTRS,
3          VK,TC,WT,Z,WATRC,WATNU,TEMP,NOSCRW,HCL,PATM,
4          PMATVAR,PRMAT,DIALIN,ETARK,
5          RJ,C75R,R75RKT,KQ
REAL*4     AREA(10),WIDTH,VOL1,VOL2,VOLBLD
COMMON /GLOECH/ETAC,WEIGHT,AEDVAO,DIA,N,PE,FDIVD,QS,TC75K,V,RJCNL,
1RJCNV,R75RCL,R75RCU,AEACCU,TC75CL,TC75CU,POWBAL,DIAACNU,
2AEACCV,TCSTRS,RJ
COMMON /PARAM/VK,TD,WT,Z,WATRU,WATNU,TEMP,NOSCRW,HCL,PATM,PMATVA,
1PRMAT,DIALIN,ETARR,AEACMN,TC75MN,SC
COMMON /AREELD/AREA
DETERMINE BLADE VOLUME BY SIMPSON INTEGRATION SCHEME OF BLADE
CROSS-SECTIONAL AREAS FROM 2/10 RADIUS OUTWARD TO TIP
VOL1=((DIA/2.0)*0.11/3.0)*(AREA(2)+(4.0*AREA(3))+(2.0*AREA(4)))+
1      (4.0*AREA(5))+(2.0*AREA(6)))+
2      (4.0*AREA(7))+(2.0*AREA(8)))+
3      (4.0*AREA(9))+AREA(10))
DETERMINE BLADE VOLUME FROM 2/10 RADIUS INWARD TO R=.18R USING
BLADE PROPELLERS OR R=.167R FOR 4,2,66 BLADE PROPELLERS USING
SIMPLE TRAPEZOIDAL INTEGRATION SCHEME
IF(.NOT.(Z.EQ.3.0))GO TO 1
GO TO 5
1 CONTINUE
IF(.NOT.(Z.EQ.4.0))GO TO 2
GO TO 5
2 CONTINUE
IF(.NOT.(Z.EQ.5.0))GO TO 3
GO TO 5
3 CONTINUE
IF(.NOT.(Z.EQ.6.0))GO TO 4
GO TO 5
4 CONTINUE
IF(.NOT.(Z.EQ.7.0))GO TO 5
GO TO 5
5 CONTINUE

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APPL C490
APPL C500
APPL C510
APPL C520
APPL C530
APPL C540
APPL C550
APPL C560
APPL C570
APPL C580
APPL C590
APPL C600
APPL C610
APPL C620
APPL C630
APPL C640

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      WIC1T=(DIA/2.0)*(C.2-C.167)
      GO TO 5
3 CONTINUE
      IF (.NOT. (Z.EQ.6.0)) GO TO 4
      WIC1T=(DIA/2.0)*(0.2-0.167)
      GO TO 5
4 CONTINUE
      WIC1T=(DIA/2.0)*(0.2-0.18)
5 CONTINUE
      VOL2=((AREA(1)+AREA(2))/2.0)*WIDTH
      CALCULATE PROPELLER BLADE VOLUME
      VOLBLD=VOL1+VOL2
      RETURN
      END

```

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SUBROUTINE ELPGWL(KT,SCWBAL)
SUBROUTINE: BLPCWL
INPUT      OUTPUT
PE
KT
DIA
N
WATRO
V
WT
TD
ETARR

SOMBAL

REAL*4      ETAD,WEIGHT,AELVAD,DIA,N,PL,PUIVL,QS,TC75R,V,
1      RJCNU,RJCNU,R75RCL,R75RCL,AEACCU,TC75CL,TC75CU,
2      FOWBZL,DIA,AEACCU,AEACCU,TCSTRS,RJ
3      VK,TC,WT,Z,WATRO,WATRO,TEMP,NCS,CRM,HCL,PATM,
4      PWATVA,PRGMAT,DIALIM,ETARR,AEACMN,TC75MN,SC,
5      KT,PEDEV,THRST,FT,SCWBAL
COMMON /GLOECH/ETAD,WEIGHT,AELVAD,DIA,N,PE,FUIVD,QS,TC75R,V,RJCNU,
1RJCNU,R75RCL,R75RCL,AEACCU,TC75CL,TC75CU,PWMBAL,DIA,
2AEACCU,TCSTRS,RJ
COMMON /PARAM/VK,TC,WT,Z,WATRO,WATRO,TEMP,NCS,CRM,HCL,PATM,PWATVA,
1PRGMAT,DIALIM,ETARR,AEACMN,TC75MN,SC
CALCULATE THRUST DEVELOPED BY EACH PROPELLER
THRST=(KT*WATRO*(DIA**4)*((N/60.0)**2))
DETERMINE HULL EFFECTIVE POWER DEVELOPED BY PROPELLER(S)
PT=(THRST*((1.0-WT)*V))/550.0
PEDEV=((1.0-TC)/(1.0-WT))*ETARR*PT)*N(CSRW)
CALCULATE CONSTRAINT VARIABLE
SOMBAL=1.0-(PEDEV/PE)
RETURN
END

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APPLC670
APPLC680
APPLC690
APPLC700
APPLC710
APPLC720
APPLC730
APPLC740
APPLC750
APPLC760
APPLC770
APPLC780
APPLC790
APPLC800
APPLC810
APPLC820
APPLC830
APPLC840
APPLC850
APPLC860
APPLC870
APPLC880
APPLC890
APPLC900
APPLC910
APPLC920
APPLC930
APPLC940
APPLC950
APPLC960
APPLC970
APPLC980
APPLC990
APPL1000
APPL1010
APPL1020
APPL1030
APPL1040
APPL1050
APPL1060
APPL1070
APPL1080
APPL1090
APPL1100
APPL1110
APPL1120
APPL1130

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DATE OF LAST REVISION: FEB 83

DEFINITION

HULL EFFECTIVE HURSEP COWER (HP)
 THRUST COEFFICIENT
 PROPELLER DIAMETER (FT)
 PROPELLER REVOLUTION RATE (RPM)
 WATER DENSITY (LB/SEC²/FT⁴)
 SHIP SPEED (FT/SEC)
 WAKE FRACTION
 THRUST DEDUCTION
 RELATIVE ROTATIVE EFFICIENCY
 CONSTRAINT VARIABLE FOR PRO-
 PELLER-DEVELOPED EFFECTIVE
 HURSEP COWER CONSTRAINT
 (SCWBALCO)

SOMBAL

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SUBROUTINE ELPCW3(KT,KC,SOWBLP,SOWBLQ)
SUBROUTINE: BLPW3
DATE OF LAST REVISION: FEB 83
INPLT      OUTPUT
KT          THRUST COEFFICIENT
KQ          TORQUE COEFFICIENT
PE          HULL EFFECTIVE HORSEPOWER (HP)
N          PROPELLER REVOLUTION RATE (RPM)
NOSCRW     DELIVERED TORQUE (FT-LBF)
WT         NUMBER OF PROPELLERS
ETARR      WAKE FRACTION
          THRUST DEDUCTION
          RELATIVE ROTATIVE EFFICIENCY
          CONSTRAINT VARIABLE FOR
          EFFECTIVE HORSEPOWER
          CONSTRAINT (SOWBLP<0)
          CONSTRAINT VARIABLE FOR
          DELIVERED POWER
          CONSTRAINT (SOWBLQ<0)

REAL*4  ETAO,WEIGHT,AEOVAD,DIA,N,PE,POIVC,QS,TC75R,V1,
1  FJCNL,RJCNL,R75RCL,R75RCLU,AEAGCL,AEAGCU,TC75CL,TC75CU,
2  FCWBL,DIA,NU,AEAGCV,TCSTRS,RJ
3  VK,TC,WT,2,WAT,WATNU,TEMP,NOSCRW,HCL,PATM,
4  PWATVA,PRMAT,DIALIM,ETARR,AEADMA,TC75MN,SC,KT,KQ,
5  PII,ETAOSP,THRST,PEDEV,CPABD,PDABD,PC,SOWBLP,SOWBLQ
COMMON  /GLDECM/ETAO,WEIGHT,AEOVAD,DIA,N,PE,POIVC,QS,TC75R,V1,NJCNL,
1  RJCNL,R75RCL,R75RCLU,AEAGCL,AEAGCU,TC75CL,TC75CU,PWBL,DIA,NU,
2  AEAGCV,TCSTRS,RJ
3  COMPMAT,7FAR,AM/VK,TC,WT,2,WATNU,WATNU,TEMP,NOSCRW,HCL,PATM,PWATVA,
4  PI=3.141592654
          CALCULATE THRUST DEVELOPED BY EACH PROPELLER
          THRST=(KT*WATRO*(DIA**4)*((N/60.0)**2))
          DETERMINE EFFECTIVE POWER DEVELOPED BY PROPELLER(S)
          PI=(THFST*((1.0-WT)*V))/550.0
          PEDEV=(((1.0-TO)/(1.0-WT))*ETARR*PT)*NOSCRW
          CALCULATE THE TORQUE ABSORBED BY PROPELLER
          CPABD=(KC*WATRO*(DIA**5)*((N/60.0)**2))

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SUBROUTINE CALCKQ(J,PDIVD,AEDVAC,Z,REYN,KQ)
SUBROUTINE: CALCKQ      DATE OF LAST REVISION: FEB 83
INPLT      OUTPUT      DEFINITION
AEDVAC      EXPANDED AREA RATIO
PDIVD      PITCH-DIAMETER RATIO
Z          NO. OF BLADES
J          ADVANCE RATIO
REYN      REYNOLDS NO. 3/4 RADIUS
          (CORRECTED FOR I/C 3/4 RADIUS
          THRUST COEFFICIENT
          KQ
REAL*4 J,PDIVD,AEDVAC,Z,REYN,KQ,KQ1,KQ2,KQ3,KQ4,KQ5,KQ6,KQ7,KQ8,
1 KQ9,KQ10,DELKQ,DELKQ1,DELKQ2,DELKQ3,REYFAC
1 FIRST, CALCULATING "KQ1" THRU "KQ10".....
KQ1=((-.0379+681)*((.00886523)*(J**2))+((-0.032241)*J*PDIVD)+
1 (-.0344778)*((PCIVD**2))+((-0.0408811)*PCIVD*AEDVAC)+
1 (-.108009)*J*PDIVC*AEDVAC)+((-0.0885381)*(J**2)*PDIVD*AEDVAC)*
2 (-.0051+696)*PCIVD*Z)+
1 (-.00209449)*J*PDIVD*Z)+((-0.00474319)*(J**2)*PDIVD*Z)+
2 (-.00263403)*((PDIVD**2)*AEDVAC*Z)+
1 (-.00315086)*J*PDIVD*AEDVAC)+((-0.0161856)*(PDIVD**3)*AEDVAC)+
2 (-.00471129)*J*(AEDVAC**2))+
1 (-.00196283)*((J**3)*(AEDVAC**2))+((-0.05042782)*PDIVD*
2 (AEDVAC**2))+((-0.030055)*(J**3)*PCIVD*(AEDVAC**2))+
1 (-.00417122)*((J**2)*PDIVD**2)*((AEDVAC**2))+
2 (-.00391722)*((PCIVD**3)*(AEDVAC**2))+
3 (-.003350024)*((PDIVD**3)*(AEDVAC**2))+((-0.0106854)*(J**3)*Z)+
1 (-.00119037)*((J**3)*PDIVD**6*(AEDVAC**2))+((-0.00313912)*(PDIVD**6)*
2 Z)+((-0.0035585)*(J**3)*AEDVAC*Z)+
1 (-.00142121)*((PDIVD**6)*AEDVAC*Z)+((-0.00383637)*J*
2 (AEDVAC**2)*Z)+((-0.0126803)*(PDIVD**2)*(AEDVAC**2)*Z)+
1 (-.00318278)*((J**2)*(PDIVD**3)*(AEDVAC**2)*Z)+
2 (-.00334268)*((PCIVD**6)*(AEDVAC**2)*Z)+
3 (-.00183491)*J*PDIVD*(Z**2))+((-0.000112451)*(J**3)*(PDIVD**2)
1 (Z**2))+((-0.000257228)*(J**3)*(PCIVD**6)*(Z**2))+
2 (-.000249551)*J*(AEDVAC*(Z**2))+((-0.00083265)*(J**2)*AEDVAC*
3 (Z**2))+
1 (-.00153334)*((PCIVD**2)*AEDVAC*(Z**2))+((-0.000302683)*
2 (PCIVD**6)*AEDVAC*(Z**2))+((-0.0001543)*(AEDVAC**2)*(Z**2))+
1 (-.000425359)*(PDIVD**3)*(AEDVAC**2)*(Z**2))+
2

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APPL2670
APPL2680
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APPL2800
APPL2810
APPL2820
APPL2830
APPL2840
APPL2850
APPL2860
APPL2870
APPL2880
APPL2890
APPL2900
APPL2910
APPL2920
APPL2930
APPL2940

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3      ((.CC0069243)*(J**5)*(PDIVD**3)*(AEDVAC**2)*(Z**2))
1      KQ10=((-0004655)*(PDIVC**6)*(AEDVAC**2)*(Z**2))+
      ((.000554194)*J*(PDIVD**6)*(AEDVAC**2)*(Z**2))
      NEXT,CALCULATE LOGARITHMIC REYNOLDS NUMBER FACTOR "REYFAC"
      WRITE(6,*,IREYNG,REYNO,REYNG
      REYFAC=ALOG10(REYNO)-0.301
      THEN,CALCULATE "DELKQ=DELKQ1+DELKQ2+DELKQ3".....
      DELKQ1=(-.000591+12)+((.00096858)*PDIVD)+
      ((-.00066654)*Z*(PDIVC**6))+((.0160818)*(AEDVAC**2))
1      DELKQ2=((-000538051)*REYFAC*PDIVD)+((-00059553)*REYFAC*
      (PDIVD**2))+((.0000782099)*(REYFAC**2)*(PDIVD**2))+
2      ((.000052155)*REYFAC*Z*AEDVAC*(J**2))
1      DELKQ3=((-0000088528)*(REYFAC**2)*Z*AEDVAC*(PDIVD**J))+
2      ((.000230171)*REYFAC*Z*(PDIVD**6))+((-00000184341)*
      (REYFAC**2)*Z*(PDIVD**6))+((-00000252)*REYFAC*
3      (AEDVAC**2))+((-000220915)*(REYFAC**2)*(AEDVAC**2))
      DELKQ=DELKQ1+DELKQ2+DELKQ3
      FINALLY,CALCULATE THICKST COEFFICIENT "KC" WHERE
      *KQ=KC1+KQ2+KQ3+KQ4+KC5+KQ6+KQ7+KQ8+KQ9+KQ10+DELKQ
      KQ=KQ1+KQ2+KQ3+KQ4+KQ5+KQ6+KQ7+KQ8+KQ9+KQ10+DELKQ
      RETURN
      END

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SUBROUTINE CALCKT(J,PDIVU,AEDVAC,Z,REYNC,KT)
SUBROUTINE: CALCKT      DATE OF LAST REVISION: FEB 83
INPUT      OUTPUT      DEFINITION
AECVAG     EXPANDED AREA RATIO
PDIVD      PITCH-DIAMETER RATIO
Z          NC. OF BLADES
J          ADVANCE RATIO
REYN       KEYNOLC'S NO. 3/4 KADIAUS
              (CORRECTED FOR I/C 3/4 RADIUS
              TFRUST COEFFICIENT
              KT
REAL*4 J,PDIVD,AEDVAC,Z,REYNU,KT1,KT2,KT3,KT4,KT5,KT6,KT7,KT8,
      DELKT,DELKT1,DELKT2,DELKT3,REYFAC
      FIRST, CALCULATING "KT1" THRU "KT8".....
      KT1=.CGEFC456+((-2G4554)*J+((-166351)*PDIVD)+
      1      (-.481457)*J*(PDIVD**2))+((-141581)*J**2)*AEDVAC
      1      +((-1444643)*Z)+((-530054)*J*(J**2)*Z)+((-143481)*PDIVD*Z)
      1      +((-105626)*J*PDIVC*Z)+((-125894)*AEDVAC*Z)+
      1      +((-105689)*J*AEDVAC*Z)+((-133698)*PDIVD**3)+((-100638407)*
      2      +((-1013271)*J*(J**2)*PDIVD**6))+((-168496)*J**3)*AEDVAC)+
      1      +((-10507214)*J*(AEDVAC**2))+((-1085455)*J*(J**2)*AEDVAC**2))+
      2      +((-10504475)*J*(J**3)*AEDVAC**2))+
      1      +((-104465)*J*(PDIVC**6)*J*(AEDVAC**2))+((-100841728)*J*(PDIVD**3)*
      2      +((-10168424)*J*(PDIVC**3)*Z)+((-100102296)*J*(PDIVD**3)*Z)
      1      +((-1031791)*J*(PDIVD**3)*AEDVAC**2))+((-101604)*J*(AEDVAC**2)*Z)+
      2      +((-100410798)*J*(PDIVD**2)*AEDVAC**2)*Z)+((-100606848)*J*(Z**2))+
      1      +((-10045815)*J*(Z**2))+
      2      +((-10025583)*J*(J**2)*Z**2))+((-100560526)*J*(J**3)*Z**2))+
      1      +((-10163652)*J*(PDIVD**2)*Z**2))+((-100328787)*J*
      2      +((-10163652)*J*(PDIVD**2)*Z**2))+((-100116502)*J*(PDIVD**6)*Z**2))+
      1      +((-100650904)*J*AEDVAC*(Z**2))+((-100421745)*J*(PDIVD**3)*AEDVAC*
      2      +((-10000565229)*J*(J**3)*PDIVD**6)*AEDVAC*(Z**2))+
      2      +((-100146564)*J*(PDIVD**3)*AEDVAC**2)*Z**2)
      NEXT, CALCULATE LOGARITHMIC REYNOLDS NUMBER FACTOR "REYFAC"
      WRITE(6,*)REYNC,REYNC
      REYFAC=ALOG10(REYNC)-0.501
      THEN, CALCULATE "DELKT=DELKT1+DELKT2+DELKT3".....

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SUBROUTINE CALCCS(KC,SCS)
SUBROUTINE: CALCCS
INPUT      OUTPUT
KQ
DIA
N
MATRO
SQS
KEAL*4
1  ETAD,WEIGHT,AEDVAG,DIA,N,PE,PDIVD,QS,TC75R,V,
2  RJCNU,RJCNU,R75RCL,R75RCL,AEACCU,TC75CL,TC75CU,
3  FCMBAL,DIA,CNU,AEACCU,TC75R,RJ,
4  VK,T,WT,7,MATRO,MATNU,TEMP,NOS,CRM,HCL,PATM,
5  PRATVA,PROMAT,DIALIM,ETARR,AEADNA,TC75MN,SC,
6  KC,SCS
COMMON /GLOECM/ETAG,WEIGHT,AEDVAG,DIA,N,PE,PDIVD,QS,TC75R,V,RJCNU,
1RJCNU,R75RCL,R75RCL,AEACCU,TC75CL,TC75CU,POMBAL,DIA,CNU,
2AEACCU,TC75R,RJ
COMMON /PARAM/VK,T,WT,7,MATRO,MATNU,TEMP,NOS,CRM,HCL,PATM,PWATVA,
1PRATVA,DIALIM,ETARR,AEADNA,TC75MN,SC
CALCULATE DELIVERED TCRCUE REQUIRED BY PROPELLER
SQS=(KC*MATFU*(CIA**5))*((N/60.0)**2))
RETURN
END

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APPL13640
APPL13650
APPL13660
APPL13670
APPL13680
APPL13690
APPL13700
APPL13710
APPL13720
APPL13730
APPL13740
APPL13750
APPL13760
APPL13770
APPL13780
APPL13790
APPL13800
APPL13810
APPL13820
APPL13830
APPL13840
APPL13850
APPL13860
APPL13870
APPL13880
APPL13890
APPL13900
APPL13910
APPL13920

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SUBROUTINE CALCPE(KT,SPE)
SUBROUTINE: CALCPE
      DATE OF LAST REVISION: FEB 83
      DEFINITION
      THRUST COEFFICIENT (FT)
      PROPELLER DIAMETER (FT)
      PROPELLER REVOLUTION RATE (RPM)
      WATER DENSITY (LBF-SEC2/FT4)
      THRUST DEDUCTION
      TAYLOR WAKE FRACTION
      VELOCITY (FT/SEC)
      EFFECTIVE POWER (HP)

      INPUT      OUTPUT
      KT
      DIA
      NATRO
      TD
      WT
      V

      SPE

      REAL*4  ETAO,WEIGHT,AEDVAO,DIA,N,PE,POIVG,QS,TC75R,V,
1            RJCNU,R75RCU,R75RCL,R75RCU,AEAOCL,TC75CL,TC75CU,
2            FOWBAL,DIA,NU,AEAOCL,TC75R,RJ,
3            VK,TI,WT,Z,NATRO,NATNU,TEMP,NOSCRW,HCL,PATM,
4            PMATVA,PROMAT,DIALIN,ETARK,AEADMN,TC75MN,SC,
5            KT,SPE,T
      COMMON  ZGLOECH/ETAO,WEIGHT,AEDVAO,DIA,N,PE,FUVID,QS,TC75R,V,RJCNU,
1            R75RCL,R75RCU,AEAOCL,TC75CL,TC75CU,POMBAL,DIA,NU,
2            AEAOCL,TC75R,RJ
      COMMON  /PAR2M/VK,TC,WT,Z,NATRO,NATNU,TEMP,NOSCRW,HCL,PATM,PMATVA,
1            PROMAT,DIALIN,ETARR,AEADMN,TC75MN,SC

      CALCULATE THRUST DEVELOPED BY PROPELLER
      T=(KT*NATRO*(DIA**4)*((N/60.0)**2))
      CALCULATE EFFECTIVE HORSEPOWER DEVELOPED BY PROPELLER
      SPE=((1.0-TC)/(1.0-WT))*((T*(1.0-WT)*V)/550.0)
      RETURN
      END

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SUBROUTINE CAVCNA(KT,SEACV)
SUBROUTINE: CAVCNA
INPUT      OUTPUT
PMTM
WATRO
PWATVA
HCL
KT
DIA
N
NOSCRW
AECVAD
SEACV

DATE OF LAST REVISION: FEB 83
DEFINITION
ATMOSPHERIC PRESSURE (PSIA)
WATER DENSITY (LBF-SEC2/FT4)
VAPORIZATION PRESSURE FOR WATER (PSIA)
DEPTH OF PROPELLER SHAFT
CENTERLINE (FT)
THRUST COEFFICIENT
PROPELLER DIAMETER (FT)
PROPELLER REVOLUTION RATE(RPM)
NO. OF BLADES
NO. OF PROPELLERS
PROPELLER EXPANDED AREA RATIO
CONSTRAINT VARIABLE FOR PROPELLER EXPANDED AREA RATIO
CONSTRAINT (SEACV<0)

REAL*4  ETAD,WEIGHT,AEDVAD,DIA,N,PE,FUIV,QS,TC75R,V,
1  RJCNL,RJCNL,R75RCL,R75RCU,AEACCU,AEACCU,TC75CL,TC75CU,
2  FCWBZL,DIA,AEACCU,TC75RCL,TC75RCL,TC75RCL,TC75RCL,
3  VK,TC,WT,Z,WATRO,WATNU,TEMP,NOSCRW,HCL,PATM,
4  F,ATVA,PROMAT,DIALIM,ETARR,AEACMA,TC75MN,SC,
5  KT,PCMN,PV,THRST,SEACMN,SEACCV
COMMON /GLOECM/ETAD,WEIGHT,AEDVAD,DIA,N,PE,FUIV,QS,TC75R,V,RJCNL,RJCNL,
1  RJCNL,R75RCL,R75RCU,AEACCU,AEACCU,TC75CL,TC75CU,PCWBZL,DIA,AEACCU,
2  AEACCU,TC75RCL,TC75RCL,TC75RCL,TC75RCL,TC75RCL,TC75RCL,TC75RCL,
1  PROMAT,DIALIM,ETARR,AEACMA,TC75MN,SC

CALCULATE DIFFERENCE BETWEEN STATIC PRESSURE AT SHAFT CENTERLINE
& WATER VAPORIZATION PRESSURE
FUMNPV=((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
THRST=(KT*WATRO*(DIA**4)*((IN/60.0)**2))
SEACMN=((1.3+(0.3*Z))*THRST)/((DIA**2)*FUMNPV)

CORRECT ACCORDING TO NUMBER OF PROPELLERS
IF (.NOT.(NOSCRW.EQ.1.0))GO TO 1

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APPI14230
 APPI14340
 APPI14350
 APPI14360
 APPI14370
 APPI14380
 APPI14390
 APPI14400
 APPI14410
 APPI14420
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 APPI14440
 APPI14450
 APPI14460
 APPI14470
 APPI14480
 APPI14490
 APPI14500
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 APPI14590
 APPI14600
 APPI14610
 APPI14620
 APPI14630
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 APPI14650
 APPI14660
 APPI14670
 APPI14680
 APPI14690
 APPI14700
 APPI14710
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 APPI14760
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 APPI14780
 APPI14790
 APPI14800

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APPI4610
APPI4820
APPI4830
APPI4840
APPI4850
APPI4860
APPI4870
APPI4880
APPI4890
APPI4900
APPI4910
APPI4920
APPI4930
APPI4940
APPI4950
APPI4960

```

```

      SEACMN=SEACMN+0.2
      GO TO 3
1 CONTINUE
      IF (.NOT. (NO$CRW.EQ.2.0)) GO TO 2
      SEACMN=SEACMN+0.1
      GO TO 3
2 CONTINUE
      SEACMN=SEACMN+0.0
3 CONTINUE
      AEACMN=SEACMN
      DETERMINE CONSTRAINT VARIABLE
      SEACV=(SEACMN/AEDVAD)-1.0
      RETURN
      END

```

CC

```

SUBROUTINE CH75RA(C75R)
SUBROUTINE: CH75RA      DATE OF LAST REVISION: FEB 83
INPLT      C75R      OUTPUT      DEFINITION
AECVAD      EXPANDED AREA RATIO
DIA      PROPELLER DIAMETER (FEET)
Z      NO. OF ELADES
      CHORD LENGTH AT 3/4 RADIUS
      (FEET)
REAL*4      ETAD,WEIGHT,AEDVAO,DIA,N,PE,FDIVD,QS,TC75R,V,
1      FJCNL,RJCNL,R75RCL,R75RCU,R75RCU,AEACCU,TC75CL,TC75CU,
2      FCMBAL,DIAACNU,AEACCU,TC75RCL,TC75RCL,TC75RCL,TC75RCL,
3      VK,TC,WT,Z,WATRO,WATNU,TEMP,NOS,CRW,HCL,PATM,
4      PHATVA,PRCMAT,DIALIM,ETARR,AEADMA,TC75MN,SC,
5      C75R
COMMON /GLOECM/ETAD,WEIGHT,AEDVAO,DIA,N,PE,FDIVD,QS,TC75R,V,RJCNL,
1RJCNL,R75RCL,R75RCU,AEACCU,TC75RCL,TC75RCL,TC75RCL,TC75RCL,
2AEACCU,TC75RCL,TC75RCL,TC75RCL,TC75RCL,TC75RCL,TC75RCL,TC75RCL,
COMMON /PARAM/VK,TC,WT,Z,WATRO,WATNU,TEMP,NOS,CRW,HCL,PATM,PHATVA,
1PRCMAT,DIALIM,ETARR,AEADMA,TC75MN,SC
      CALCULATE CHORD LENGTH AT 3/4 RADIUS USING RELATION (17),REF 2
C75R=(2.073*AEDVAO*CIAN)/Z
RETURN
END

```

APPI14590
 APPI15000
 APPI15010
 APPI15020
 APPI15030
 APPI15040
 APPI15050
 APPI15060
 APPI15070
 APPI15080
 APPI15090
 APPI15100
 APPI15110
 APPI15120
 APPI15130
 APPI15140
 APPI15150
 APPI15160
 APPI15170
 APPI15180
 APPI15190
 APPI15200
 APPI15210
 APPI15220
 APPI15230
 APPI15240
 APPI15250
 APPI15260
 APPI15270


```

4 5 REAL*4 FMAI1A,PRCMAT,CIALIN,ETARR,
REAL*4 RJCNU,R75RCL,XCG(10),KIXXNA(10),RIYVNA(10)
REAL*4 SUMSV,SUMSVR,SUMSVT,SUMSVA
REAL*4 SMALLT(10),SMALLA(10),SMALLT(10),SMALMA(10),
1 SINBET(10),CCSBET(10),
2 SUM(10),SUMR(10),SUMT(10),SUMA(10),SMQ(10),
3 VULO(10),XBRCL(10),BIGTO(10),BIGAO(10),SMPO(10),RADIUS
REAL*4 CMCBN(10),CMCBL(10),BIGNO(10),RADIUS
INTEGER*4 IFIRF1,KCUNT,I
COMMON /GLDEH/ETAO,WEIGHT,AEDVAD,DIA,N,PE,EDIVD,US,TC75R,V,RJCNL,
1RJCNU,R75RCL,R75RCL,AEAGCL,AEACU,TC75CL,TC75CU,POMBAL,CIAONU,
2AEACU,TC75R,RJ,TC,WT,Z,MATRU,MATNU,TEMP,NCSCRM,HCL,PATM,PWATVA,
1PRCMAT,CIALIN,ETARR,AEADMN,TC75MN,SC
COMMON /AREELD/AREA
COMMON /CGX/XCG
COMMON /CGY/YCG
COMMON /AZMCMX/RIYVNA
COMMON /AZMCMY/RIXXNA
COMMON /CFGEHN/CMCBN
COMMON /CFGEHL/CMCBL
COMMON /CFGFD/BIGNO
PII=3.141592654

CALCULATE RAKE ANGLE IN RADIAN
ETA=15.0*(PII/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 TYPE 2 BRONZE .305
4 NI-AL BRUNZE .278
5 STAINLESS STEEL .283

IF (PRCMAT.EC.1) CIND=.260
IF (PRCMAT.EC.2) CIND=.284
IF (PRCMAT.EC.3) CIND=.305
IF (PRCMAT.EC.4) CIND=.278
IF (PRCMAT.EC.5) CIND=.283

DETERMINE VALUES FOR...
SMALLI(1) DISTANCE TO THE PITCH REFERENCE LINE, ALONG THE
PROPELLER RADII, WITH RESPECT TO A LINE NORMAL

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CCCCCCCCCCCCCCCC
SMALLA(IR)
SMALLT(IR)
... FOR EACH BLADE SECTION ALONG THE PROPELLER RADIUS
DO 9 IR=2,10
  IF(.NOT.(Z.EQ.4.0))GO TO 7
  IF(.NOT.(IR.EQ.2))GO TO 2
    GC TO 6
    CCNTINUE
    IF(.NOT.(IR.EQ.3))GO TO 3
      GC TO 6
      CCNTINUE
      IF(.NOT.(IR.EQ.4))GO TO 4
        GC TO 6
        CCNTINUE
        IF(.NOT.(IR.EQ.5))GO TO 5
          GC TO 6
          CCNTINUE
          RF=1.00
          CCNTINUE
          DENOM=SQRT((RF*PDIVD)**2)+(PII**2)
          SINBET(IR)=(RF*PDIVD)/DENOM
          CCSBET(IR)=(PII)/DENOM
          GC TO 6
          CCNTINUE
          DENOM=SQRT((PDIVC**2)+(PII**2))
          SINBET(IR)=(PDIVC)/DENOM
          CCSBET(IR)=(PII)/DENOM
          CCNTINUE
          SMALLI(IR)=(DIA/2.0)*(FLOAT(IR)/10.0)*(TAN(ETA))
          SMALLA(IR)=(XCG(IR)*SINBET(IR))+(YCG(IR)*COSBET(IR))
          SMALLT(IR)=(XCG(IR)*CCSBET(IR))-(YCG(IR)*SINBET(IR))
  IF(.NOT.(IR.EQ.10))GO TO 9

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```

APPI6260
APPI6270
APPI6280
APPI6290
APPI6300
APPI6310
APPI6320
APPI6330
APPI6340
APPI6350
APPI6360
APPI6370
APPI6380
APPI6390
APPI6400
APPI6410
APPI6420
APPI6430
APPI6440
APPI6450
APPI6460
APPI6470
APPI6480
APPI6490
APPI6500
APPI6510
APPI6520
APPI6530
APPI6540
APPI6550
APPI6560
APPI6570
APPI6580
APPI6590
APPI6600
APPI6610
APPI6620
APPI6630
APPI6640
APPI6650
APPI6660
APPI6670
APPI6680
APPI6690
APPI6700
APPI6710
APPI6720
APPI6730

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SUBROUTINE COEFS(SJ,R75R,KT,KQ)
SUBROUTINE: COEFS
INFLT      OUTPUT
AEDVAD
PDIVD
Z
SJ
R75R
KT
KQ
REAL*4  ETAD,WEIGHT,AEDVAD,DIA,N,PE,PDIVC,QS,TC75R,V,
1  RJCNU,RJCNU,R75RCU,R75RCU,AEADCL,AEADCL,TC75CL,TC75CU,
2  FOWBAL,DIA,AEADCL,AEADCL,TC75CL,TC75CU,
3  VK,TC,WT,Z,WATRC,WATNU,TEMP,NOS,CRW,HCL,PAIM,
4  PMATVAT,PRMAT,DIALIN,ETARR,AEADCL,TC75CL,TC75CU,
5  R75R,KT,KQ,SJ
COMMON /GLOECL/ETAD,WEIGHT,AEDVAD,DIA,N,PE,PDIVD,QS,TC75R,V,RJCNU,
1  RJCNU,R75RCU,R75RCU,AEADCL,AEADCL,TC75CL,TC75CU,POWBAL,DIA,
2  AEADCL,TC75CL,TC75CU,POWBAL,DIA,
3  COMMON /PARAM/VK,TD,WI,Z,WATRO,WATNU,TEMP,NOS,CRW,HCL,PAIM,PMATVAT,
1  PRMAT,DIALIN,ETARR,AEADCL,TC75CL,TC75CU,POWBAL,DIA,
DATE OF LAST REVISION: FEB 63
DEFINITION
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
TORQUE COEFFICIENT

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APPI 17640
APPI 17650
APPI 17660
APPI 17670
APPI 17680
APPI 17690
APPI 17700
APPI 17710
APPI 17720
APPI 17730
APPI 17740
APPI 17750
APPI 17760
APPI 17770
APPI 17780
APPI 17790
APPI 17800
APPI 17810
APPI 17820
APPI 17830
APPI 17840
APPI 17850
APPI 17860
APPI 17870
APPI 17880
APPI 17890
APPI 17900
APPI 17910
APPI 17920
APPI 17930
APPI 17940
APPI 17950
APPI 17960
APPI 17970

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SUBROUTINE LICNUA(SIACNU)
SUBROUTINE: DICNUA
  INPUT      OUTPUT
  DIA
  DIALIM

  SIACNU

  REAL*4  ETAD,WEIGHT,AEDVAV,DIA,N,PE,FDIVD,QS,TC75CL,TC75CU,
1  RJCNU,RJCNU,R75RCL,R75RCU,AEADCL,AEADCU,TC75CL,TC75CU,
2  FCMBAL,DIAACNU,AEADCV,TCSTRS,RJ,
3  VK,TCWT,Z,WATRC,WATNU,TEMP,NOSCRW,HCL,PAIM,
4  PMATVA,PROMAT,DIALIM,ETARR,AEACMN,TC75MN,SC,
5  SIACNU

  COMMON /GLOFCM/ETAC,WEIGHT,AEDVAV,DIA,N,PE,FDIVD,QS,TC75R,V,RJCNU,
1  RJCNU,R75RCL,R75RCU,AEADCL,AEADCU,TC75CL,TC75CU,POMBAL,DIAACNU,
2  AEACCV,TCSTRS,RJ
  COMMON /PARAM/VK,TD,WI,Z,WATRO,WATNU,TEMP,NOSCRW,HCL,PAIM,PMATVA,
1  PROMAT,DIALIM,ETARR,AEACMN,TC75MN,SC

  DETERMINE CONSTRAINT VARIABLE CP PROPELLER DIAMETER'S UPPER BOUND
  CONSTRAINT

  SIACNU=(DIA/DIALIM)-1.0
  RETURN
  ENC

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APPI18000
APPI18010
APPI18020
APPI18030
APPI18040
APPI18050
APPI18060
APPI18070
APPI18080
APPI18090
APPI18100
APPI18110
APPI18120
APPI18130
APPI18140
APPI18150
APPI18160
APPI18170
APPI18180
APPI18190
APPI18200
APPI18210
APPI18220
APPI18230
APPI18240
APPI18250
APPI18260
APPI18270
APPI18280

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GO TO 6
5 CONTINUE
  AEACCL=0.35
  AEACUP=1.05
6 CONTINUE
  DETERMINE CONSTRAINT VARIABLES FOR EXPANDED AREA RATIO CONSTRAINT
  AEACCL=AEADLC-AEDVAC
  AEACCU=AECDVAD-AEADUP
  DETERMINE CONSTRAINT VARIABLES FOR ELAGE THICKNESS-TU-CHORD RATIO
  CONSTRAINT
  TC75LO=(0.5)*((0.0185-0.00125*Z)*Z)/((2.073*AEACUP))
  TC75UP=(4.0)*((0.0185-0.00125*Z)*Z)/((2.073*AEADLO))
  TC75CL=TC75LO-TC75R
  TC75CU=TC75H-TC75UP
  RETURN
END

```

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APPL16790
APPL16800
APPL16810
APPL16820
APPL16830
APPL16840
APPL16850
APPL16860
APPL16870
APPL16880
APPL16890
APPL16900
APPL16910
APPL16920
APPL16930
APPL16940
APPL16950
APPL16960
APPL16970
APPL16980

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SUBROUTINE HYDLC(KL,KT)
SUBROUTINE: HYDLC
INPLT      OUTPUT
DIA         PROPELLER DIAMETER (FT)
N           PROPELLER REVOLUTION RATE (RPM)
POIVD      PITCH-DIAMETER RATIO
KT         THRUST COEFFICIENT
KQ         WATER DENSITY (LBF-SEC2/FT4)
WATRO      NC OF PROPELLER BLADES
Z           HYDRODYNAMIC MOMENTS PARALLEL
           TO BLADE SECTION PITCH REFERENCE (CHCRD) LINE (FT-LBF)
           HYDRODYNAMIC MOMENTS NORMAL
           TO BLADE SECTION PITCH REFERENCE (CHCRD) LINE (FT-LBF)

COMMON/HYDROMN/
COMMON/HYDROMML/

REAL*4      ETAO, WEIGHT, AEDVAD, DIA, PDI, PDIYC, QS, TC75R, V,
1            FCHNL, RJCNU, R75RCL, R75KCU, AEAUCL, AEAUCU, TC75CL, TC75CU,
2            FCHBAL, DIACNU, AEAUCV, TC75KS,
3            VKITL, WT, Z, WATRO, WATNU, TEMP, NOSCRW, HCL, PATM,
4            PWATVA, PROMAT, DIALIM, ETARR,
5            RJCNU, R75RCL, R75KCU, AEAUCU, TC75CL, TC75CU, PDMBAL, DIACNU,
1            AEAUCV, TC75KS, RJCNU, PDI, PDIYC, QS, TC75R, V, RJCNU,
2            AEAUCV, TC75KS, RJCNU, PDI, PDIYC, QS, TC75R, V, RJCNU,
1            PROMAT, DIALIM, ETARR,
COMMON /HYMCMN/HMPL
COMMON /HYMCHL/HMPL
PII=3.141592654

Determine values along the propeller radius of various functions
of XO and XF defined by bracketed expressions in relations (4),
(9) and (19), REF E
DO 1 IR=2,10
  XO=(FCHNL*(IR))/10.0
  PH11(11)=((1.0/15.0)*
1            ((8.0+(4.0*XO)+(3.0*(XC**2))-(15.0*(XU**3))))*
2            (SQRT(1.0-XO))
  PH12(11)=((2.0/45.0)*

```

```

APPL15010
APPL15020
APPL15030
APPL15040
APPL15050
APPL15060
APPL15070
APPL15080
APPL15090
APPL15100
APPL15110
APPL15120
APPL15130
APPL15140
APPL15150
APPL15160
APPL15170
APPL15180
APPL15190
APPL15200
APPL15210
APPL15220
APPL15230
APPL15240
APPL15250
APPL15260
APPL15270
APPL15280
APPL15290
APPL15300
APPL15310
APPL15320
APPL15330
APPL15340
APPL15350
APPL15360
APPL15370
APPL15380
APPL15390
APPL15400
APPL15410
APPL15420
APPL15430
APPL15440
APPL15450
APPL15460
APPL15470
APPL15480

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CCCCC

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1      (8.0-(8.0*X0)-(3.0*(X0**2))-(2.0*(X0**3)))+
2      (5.0*(X0**4)))
3      (SQRT(1.0-X0))
1      GAP2(IF)=((2.0/15.0)*
2      (4.0-(5.0*X0)-(2.0*(X0**2))+(3.0*(X0**3))))*
3      (SQRT(1.0-X0))
1 CONTINUE
      CALCULATE THRUST DEVELOPED BY PROPELLER
      T=(KT*WATRO*(DIA**4)*((N/60.0)**2))
      CALCULATE TORQUE REQUIRED BY PROPELLER
      Q=(KQ*WATRO*(DIA**5)*((N/60.0)**2))
      CALCULATE BENDING MOMENTS DUE TO THRUST ( BMT(IR) ) AND TORQUE
      ( BMTQ(IR) ) ALONG THE PROPELLER RADIUS USING RELATIONS (10) AND
      (26) RESPECTIVELY, REF 8
      DO 2 IR=2,11
        BMT(IR)=((T*(DIA/2.0))/2.1)*(PHI2(IR)/PHI1(2))
        BMTQ(IR)=(Q/2.1)*(GAP2(IR)/PHI1(2))
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 RELATIONS (42) AND (43), REF 8 .
      REMEMBER TO ACCOUNT FOR PITCH REDUCTION OF FOUR BLADE (Z=4.0)
      PROPELLERS
      DO 10 IR=2,10
        IF(.NOT.(Z.EQ.4.0))GO TO 6
        IF(.NOT.(IR.EQ.2))GO TO 3
        RF=0.822
        GC TO 7
        CCNTINUE
        IF(.NOT.(IR.EQ.3))GO TO 4
        RF=0.887
        GC TO 7
        CCNTINUE
        IF(.NOT.(IR.EQ.4))GO TO 5
        RF=0.950
        GC TO 7
        CCNTINUE
        IF(.NOT.(IR.EQ.5))GO TO 6
        RF=C.992
        GC TO 7

```

```

APPL15490
APPL15500
APPL15510
APPL15520
APPL15530
APPL15540
APPL15550
APPL15560
APPL15570
APPL15580
APPL15590
APPL15600
APPL15610
APPL15620
APPL15630
APPL15640
APPL15650
APPL15660
APPL15670
APPL15680
APPL15690
APPL15700
APPL15710
APPL15720
APPL15730
APPL15740
APPL15750
APPL15760
APPL15770
APPL15780
APPL15790
APPL15800
APPL15810
APPL15820
APPL15830
APPL15840
APPL15850
APPL15860
APPL15870
APPL15880
APPL15890
APPL15900
APPL15910
APPL15920
APPL15930
APPL15940
APPL15950
APPL15960

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AD-A132 414

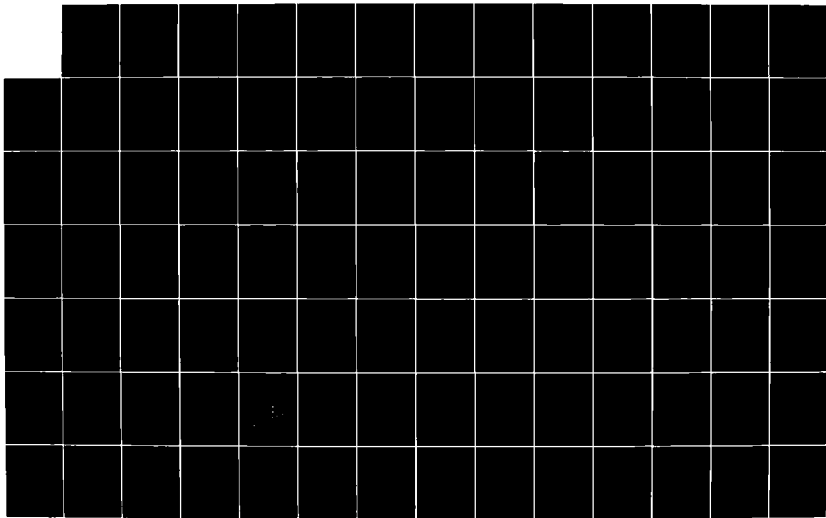
PRELIMINARY PROPELLER SELECTION USING THE WAGENINGEN
B-SCREW SERIES AND A GENERAL PURPOSE NON-LINEAR
OPTIMIZER(U) NAVAL POSTGRADUATE SCHOOL MONTEREY CA
M P SMITH JUN 83

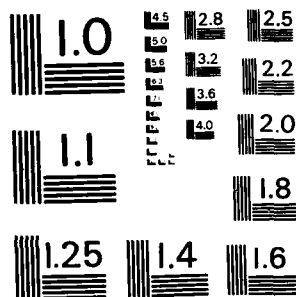
3/4

UNCLASSIFIED

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NL





MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS - 1963 - A

APP1\$570
 APP1\$580
 APP1\$590
 APP2C000
 APP2C010
 APP2C020
 APP2C030
 APP2C040
 APP2C050
 APP2C060
 APP2C070
 APP2C080
 APP2C090
 APP2C100
 APP2C110
 APP2C120
 APP2C130
 APP2C140
 APP2C150

```

6      CCNTINUE
      RF=1.00
7      CCNTINUE
      DENOM=SQRT((RF*PDIVD)**2)+(PII**2))
      HAPN(IR)=(BMT(IR))*((PII/DENOM))+
1      (BMQ(IR))*((RF*PDIVD)/DENOM))-
1      HAPL(IR)=(BMT(IR))*((PII/DENOM))+
      (BMQ(IR))*((RF*PDIVD)/DENOM))-
      GC TC
8      CCNTINUE
      DENOM=SQRT((PCIVC**2)+(PII**2))
      HAPN(IR)=(BMT(IR))*((PII/DENOM))+
1      (BMQ(IR))*((PCIVD)/DENOM))-
1      HAPL(IR)=(BMT(IR))*((PII/DENOM))+
      (BMQ(IR))*((PCIVD)/DENOM))-
9      CCNTINUE
10     CCNTINUE
      RETURN
      END
  
```

```

SUBROUTINE JCNA(RJ,RJCNL,RJCNU)
SUBROUTINE: JCNA
  INPUT      OUTPUT
  RJ          RJCNL
              RJCNU

  REAL*4 RJ,RJCN,RJCNL,RJCNU
  DETERMINE CCNSTRANT VARIABLE FOR ADVANCE CCEFFICIENT CCNSTRANT
  RJCCN=RJ/1.6
  RJCNL=C.C-RJCCN
  RJCNU=RJCCN-1.0
  RETURN
  END

```

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APP2C180
APP2C190
APP2C200
APP2C210
APP2C220
APP2C230
APP2C240
APP2C250
APP2C260
APP2C270
APP2C280
APP2C290
APP2C300
APP2C310
APP2C320
APP2C330
APP2C340
APP2C350
APP2C360
APP2C370
APP2C380
APP2C390

```

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DATE OF LAST REVISION: FEB 83
DEFINITION
ADVANCE COEFFICIENT
CCNSTRANT VARIABLE FOR AD-
VANCE COEFFICIENT(LOWER BOUND
(RJCNL<0)
CCNSTRANT VARIABLE FOR AD-
VANCE COEFFICIENT(UPPER BOUND
(RJCNU)

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APP20420
 APP20430
 APP20440
 APP20450
 APP20460
 APP20470
 APP20480
 APP20490
 APP20500
 APP20510
 APP20520
 APP20530
 APP20540
 APP20550
 APP20560
 APP20570
 APP20580
 APP20590
 APP20600
 APP20610
 APP20620

DATE OF LAST REVISION: FEB 83
 DEFINITION
 ADVANCE RATIO
 THRUST COEFFICIENT
 TORQUE COEFFICIENT
 OPEN WATER EFFICIENCY

SUBROUTINE CPWEFF(RJ,KT,KQ,ETAO)
 SUBROUTINE: CPWEFF
 INPUT OUTPUT
 RJ
 KT
 KQ
 ETAO
 REAL*4 RJ,KT,KQ,ETAC,PII
 PII=3.141592654
 CALCULATE OPEN WATER EFFICIENCY
 IF (KT.LE.0.0) KT=0.0
 IF (KQ.LE.0.0) KQ=0.0001
 ETAC=(RJ*KT)/(2.0*PII*KQ)
 RETURN
 END

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```

SUBROUTINE FEYCN(R75R,R75RCL,R75RCU)
SUBROUTINE: REYCN
  INPUT      OUTPUT
  R75R      R75RCL
            R75RCU

  REAL*4 R75R,R75RCN,R75RCL,R75RCU
  DETERMINE CONSTRAINT VARIABLE FOR CORRECTED REYNOLDS NO. CONSTRAINT
  R75RCN=R75R/200000.0
  R75RCL=1.0-R75RCN
  R75RCU=R75RCN-100.0
  RETURN
END

```

APP20570
 APP20580
 APP20590
 APP21000
 APP21010
 APP21020
 APP21030
 APP21040
 APP21050
 APP21060
 APP21070
 APP21080
 APP21090
 APP21100
 APP21110
 APP21120
 APP21130
 APP21140
 APP21150
 APP21160
 APP21170
 APP21180
 APP21190
 APP21200

DATE OF LAST REVISION: FEB 83
 DEFINITION
 REYNOLDS NO. $3/4$ RADIUS
 (CORRECTED FOR T/C $3/4$ RADIUS
 CONSTRAINT VARIABLE FOR KEY-
 NGDS NO. (CORRECTED)
 (LOWER BOUND) (R75RCL<0)
 CONSTRAINT VARIABLE FOR KEY-
 NGDS NO. (CORRECTED)
 (UPPER BOUND) (R75RCU<0)

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SUBROUTINE FEY75R(C75R,R75R)
 SUBROUTINE: REY75R
 DATE OF LAST REVISION: FEB 83
 INPUT OUTPUT
 C75R C75R LENGTH AK 3/4 RADIUS
 N DIA PRCPLELLER REVOLUTIONS (RPM)
 Z TC75R NO. OF BLADES
 AEDVAD BLADE THICKNESS-TO-
 WATNU EXPANDED AREA RATIO
 R75R KINEMATIC VISCOSITY
 REYNOLDS NO. AT 3/4 RADIUS
 CORRRECTED FOR EFFECTS
 BLADE THICKNESS
 DIVID, QS, TC75R, V,
 AEDVAD, AEDVAD, TC75R, TC75R, TC75R,
 RJCNU, RJCNU, R75R, R75R, R75R, R75R, R75R, R75R,
 FCWBL, DIACNU, AEDVAD, TC75R, R75R, R75R, R75R, R75R,
 VK, TC, W, T, Z, WATNU, WATNU, T, T, T, T, T, T, T, T,
 FLAT, VA, PRGMAT, DIACNU, T, T, T, T, T, T, T, T,
 C75R, PI, VA, R75R, R75R, R75R, R75R, R75R, R75R,
 COMMON /GLOECH/ETAO, WEIGHT, AEDVAD, DIA, N, PE, PDIVD, QS, TC75R, V, RJCNU,
 RJCNU, R75R, R75R, R75R, R75R, R75R, R75R, R75R,
 AEDVAD, TC75R, R75R, R75R, R75R, R75R, R75R, R75R,
 COMMON /PARAM/VK, TC, W, T, Z, WATNU, WATNU, T, T, T, T, T, T, T, T,
 PRGMAT, DIACNU, AEDVAD, TC75R, R75R, R75R, R75R, R75R,
 PI=3.141592654
 CALCULATE SPEED OF ADVANCE
 VA=V*(1.0-C-W)
 CALCULATE UNCORRECTED REYNOLDS NUMBER AT 3/4 PROPELLER RADIUS
 USING RELATION (10), REF 2
 R75R=VA*(1.0/WATNU)*C75R*SQR((VA**2)+(1.75*PI*(N/60.0)*DIA)**2)
 DETERMINE BLADE THICKNESS-TO-CHORD RATIO BASED ON A SPECIFIC "Z"
 "AEDVAD" USING RELATION (11), REF 2
 TC75R=VA*(1.0-C-W)*C75R*(1.0/((1.0/2.073*AEDVAD)
 DETERMINE REYNOLDS NUMBER AT 3/4 RADIUS, CORRECTED FOR BLADE
 THICKNESS-TC-CHORD RATIO "TC75R", USING RELATION (12), REF 2

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NUM=1.0*(2.0*IC75WS)
DENCM=1.0*(2.0*IC75R)
R75R=EXP(4.0052+((SQRT(NUM/DENCM))*(ALCG(R75RUN)-4.6052)))
RETURN
END

```

SUBROUTINE FJCAL(J)
SUBROUTINE: RJCAL
INPLT          CLTPLT
V              J
DIA
N
WT
REAL*4  ETAD,WEIGHT,AEDVAO,DIA,N,PE,PDIVC,QS,TC75K,V,
1      RJCNU,RJCNU,R75FCL,R75RCU,AEAOCL,AEACCU,TC75CL,TC75CU,
2      FOWBAL,DIAACNU,AEACCV,TCSTKS,RJ,
3      VK,TC,WT,Z,WATRO,WATNU,TEMP,NGSCRW,HCL,PATM,
4      PMATVA,PRCHMAT,DIALJM,ETARK,AEADOMN,TC75MN,SC,
5      J
COMMON /GLOECM/ETAC,WEIGHT,AEDVAO,DIA,N,PE,FDIVD,QS,TC75R,V,RJCNU,
1      RJCNU,R75RCU,AEACCL,AEADCU,TC75CL,TC75CU,POMBAL,DIAACNU,
2      AEACCV,TCSTKS,RJ
COMMON /PARAM/VK,TD,WI,Z,WATRO,WATNU,TEMP,NGSCRW,HCL,PATM,PMATVA,
1      PRCHMAT,DIALJM,ETARR,AEACMN,TC75MN,SC
CALCULATE ADVANCE RATIO
J=(V*(1.0-WI))/(DIA*(N/60.0))
RETURN
END

```

APP21780
 APP21790
 APP21800
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 APP21940
 APP21950
 APP21960
 APP21970
 APP21980
 APP21990
 APP22000
 APP22010
 APP22020
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 APP22050
 APP22060
 APP22070

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SUBROUTINE FNCAL(RN)
SUBROUTINE: RNCAL
INPUT          OUTPUT
V             DIA
RJ            RJ
WT           WT
RN
REAL*4  ETAO,WEIGHT,AEDVAO,DIA,N,PE,POIVD,QS,TC75R,V,
1      RJCNU,RJCNU,R75FCL,R75RCU,AEAOCL,TC75CL,TC75CU,
2      POMBAL,DIA,CNU,AEAOCL,V,TCSTKS,RJ,
3      VK,TC,WT,Z,WATRO,WATNU,TEMP,NCSCRW,HCL,PATM,
4      PMAIVA,PROMAT,DIALIM,ETARK,AEACMN,TC75MN,SC,
5      RN
COMMON /GLOECM/ETAO,WEIGHT,AEDVAO,DIA,N,PE,POIVD,QS,TC75R,V,KJCNU,
1      RJCNU,R75FCL,R75RCU,AEAOCL,TC75CL,TC75CU,POMBAL,DIA,CNU,
2      AEACCV,TCSTKS,RJ
COMMON /PARAM/VK,TC,WT,Z,WATRO,WATNU,TEMP,NCSCRW,HCL,PATM,PMAIVA,
1      PROMAT,DIALIM,ETARK,AEACMN,TC75MN,SC
CALCULATE PFCPELLER REVOLUTION RATE
RN=60.C*((V*(1.0-WT))/(DIA*KJ))
RETRN
ENC

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APP222100
 APP222110
 APP222120
 APP222130
 APP222140
 APP222150
 APP222160
 APP222170
 APP222180
 APP222190
 APP222200
 APP222210
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 APP222230
 APP222240
 APP222250
 APP222260
 APP222270
 APP222280
 APP222290
 APP222300
 APP222310
 APP222320
 APP222330
 APP222340
 APP222350
 APP222360
 APP222370
 APP222380
 APP222390

DATE OF LAST REVISION: FEB 83

DEFINITION

VELOCITY (FT/SEC)
 PROPELLER DIAMETER (FEET)
 ADVANCE RATIO
 WAKE FRACTION
 PROPELLER REVOLUTION RATE(RPM)

RN

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[illegible]

[illegible]

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COMMON /STRES1/
COMMON /STRES2/
COMMON /STRES3/
COMMON /STRES4/

DIRECT STRESS AT CRITICAL
POINT 1 AT BLADE SECTIONS
ALONG THE PROPELLER RADIUS
(LBFF/FT**2)
DIRECT STRESS AT CRITICAL
POINT 2 AT BLADE SECTIONS
ALONG THE PROPELLER RADIUS
(LBFF/FT**2)
DIRECT STRESS AT CRITICAL
POINT 3 AT BLADE SECTIONS
ALONG THE PROPELLER RADIUS
(LBFF/FT**2)
DIRECT STRESS AT CRITICAL
POINT 4 AT BLADE SECTIONS
ALONG THE PROPELLER RADIUS
(LBFF/FT**2)

REAL*4 AREA(10), R1XXNA(10), R1YYNA(10), W1(10), W2(10), W3(10), W4(10),
1 U1(10), U2(10), U3(10), U4(10), CMCBN(10), CMGBL(10), BIGNO(10),
2 FMFN(10), FMPL(10), CMGBN(10), CMGBL(10), TUBML(10),
1 SIGCF(10), SIG2(10), SIG3(10), SIG4(10)
INTEGER*4 IF
COMMON /AREELD/AREA
COMMON /VAL11/U1
COMMON /VAL12/U2
COMMON /VAL13/U3
COMMON /VAL14/U4
COMMON /VAL11/W1
COMMON /VAL12/W2
COMMON /VAL13/W3
COMMON /VAL14/W4
COMMON /A2MCMX/R1XXNA
COMMON /A2MCMY/R1YYNA
COMMON /FYMCMN/FMPL
COMMON /CFGEMN/CMCBN
COMMON /CFGEML/CMGBL
COMMON /CFGFC/BIGNO
COMMON /STRES1/SIG1
COMMON /STRES2/SIG2
COMMON /STRES3/SIG3
COMMON /STRES4/SIG4

CALCULATE DIRECT STRESS (LBFF/FT**2) DUE TO CENTRIFUGAL FORCE FOR
BLADE SECTIONS ALONG THE PROPELLER RADIUS
DO 1 IR=2,9
1 SIGCF(IR)=BIGNO(IR)/AREA(IR)

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SUBROUTINE STRCNA(KC,C75R,SCSTKS)
  INPUT          OUTPUT
  PRCPAT
  DIA
  N
  PDIVD
  KQ
  C75R
  NOSCRW
  TC75R

  DEFINITION
  PROPELLER MATERIAL IDENTIFIER
  1: CAST IRON
  2: TYPE 2 BRONZE
  3: TYPE 4 NI-AL BRONZE
  4: STAINLESS STEEL
  5: STAINLESS STEEL
  PROPELLER DIAMETER (FT)
  PROPELLER REVOLUTION RATE (RPM)
  PITCH-DIAMETER RATIO
  TORQUE COEFFICIENT
  CHORD LENGTH 3/4 RADIUS (FT)
  NO. OF PROPELLERS
  BLADE THICKNESS-TU-CHORD RATIO
  3/4 RADIUS
  CLNSTRANT VARIABLE FOR BLADE
  THICKNESS-TU-CHORD RATIO 3/4
  RADIUS CCONSTRAINT (TCSTRSCO)

  SCSTKS

  REAL*4  EIAO,WEIGHT,AEQV,DIA,N,PE,POI,VC,QS,TC75R,V,
  RJCNU,RJCNU,R75RCL,R75RCL,AEACCU,TC75CL,TC75CU,
  FCWBL,DIACNU,AEACCV,TCSTKS,RJ,
  VKTCL,WT,Z,WATRC,WATNU,TEMP,NOSCRW,HCL,PATM,
  PHATLA,PRCPAT,DIACNU,ETARR,AEACCU,TC75CL,TC75CU,
  C75R,KQ,PII,SC,CABS,RB,PABSRB,FACID,FACIN,TC75R,V,RJCNU,
  COMMON /GLOECH/EIAO,WEIGHT,AEQV,DIA,N,PE,POI,VC,QS,TC75R,V,RJCNU,
  1RJCNU,R75RCL,R75RCL,AEACCU,TC75CL,TC75CU,POMBAL,DIACNU,
  2AEACCV,TCSTKS,RJ
  COMMON /FARIM/VK,TC,WT,Z,WATRC,WATNU,TEMP,NOSCRW,HCL,PATM,PWATVA,
  1PRCPAT,DIACNU,ETARR,AEACCU,TC75CL,TC75CU,
  PII=3.141592654

  DETERMINE MAXIMUM ALLOWABLE STRESS (PSI) BASED ON NUMBER OF PRO-
  PELLERS AND MATERIAL IDENTIFIER

  IF(.NOT.(NOSCRW.EQ.1.0)) GO TO 1
  IF(FRCPAT.EQ.1.0) SC=3600.0
  IF(FRCPAT.EQ.2.0) SC=5515.0
  IF(FRCPAT.EQ.3.0) SC=7200.0
  IF(FRCPAT.EQ.4.0) SC=8910.0
  IF(FRCPAT.EQ.5.0) SC=5400.0
  GO TO 2
  1 CONTINUE
  IF(FRCPAT.EQ.1.0) SC=3950.0
  IF(FRCPAT.EQ.2.0) SC=6265.0

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APP24760
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APP24960
APP24970
APP24980
APP24990
APP25000
APP25010
APP25020

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      IF (PROPAT.EQ.3.0) SC=7585.0
      IF (PROPAT.EQ.4.0) SC=9430.0
      IF (PROPAT.EQ.5.0) SC=5500.0
2  CONTINUE
      DETERMINE ABSORBED POWER FOR EACH PROPELLER
      WABSRB=ABS(MQ*WATRC*(DIA**5)*((N/60.0)**2))
      PABSRB=(2.0*PI*I*QABSRB*N)/33000.0
      CALCULATE MINIMUM REQUIRED BLADE THICKNESS-TO-CHORD RATIO AT 3/4
      BLADE RADIUS USING RELATION (16), REF 2
      FAC10=SC*((DIA*N)**2)/(12.788)
      FAC2D=4.123*N*(C/A**3)
      FAC1N=(2375.C-(1125.0*PUIVD))*PABSRB
      T75MIN=((FAC1N/(FAC2C*FAC1D))**0.33333)*0.211*U.00281*DIA
      TC75MN=T75MIN/C75R
      DETERMINE CONSTRAINT VARIABLE FOR BLADE THICKNESS-TO-CHORD RATIO
      CONSTRAINT
      SCSTR5=(TC75MN/TC75R)-1.0
      RETURN
      END

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2AEACCV,TCSTFS,RJ
COMMON /FARIM/VK,TC,WT,2,WATRU,WATNL,TEMP,NCSCRW,HCL,PATM,PWATVA,
1PRGMAT,CIALIM,ETARR,AEACMN,TC75MN,SC
COMMON /THICD,TCOR,11XR,T20K,13UR,14OR,15OR,16OR,17OK,175R,18OR,
1T9OR,T1CCR,FAT
COMMON /AREELD/AREA
COMMON /CGX/YCG
COMMON /CGY/YCG
COMMON /CRDINT/CR
COMMON /VAL1/U1
COMMON /VAL2/U2
COMMON /VAL3/U3
COMMON /VAL4/U4
COMMON /VAL1/W1
COMMON /VAL2/W2
COMMON /VAL3/W3
COMMON /VAL4/W4
COMMON /A2MCMX/R1YNA
COMMON /A2MCMY/R1XNA
COMMON /FYMCMN/HMPN
COMMON /HYMCMH/HMPL
COMMON /CFGEMN/CMCBN
COMMON /CFGEHL/CMCBL
COMMON /CFGFU/BIGNO
COMMON /STRES1/SIG1
COMMON /STRES2/SIG2
COMMON /STRES3/SIG3
COMMON /STRES4/SIG4
DETERMINE MAXIMUM ALLOWABLE STRESS (PSI) BASED UPON THE NUMBER OF
PROPELLERS AND TYPE OF MATERIAL
IF (.NOT. (NOSCKW.EQ.1.0)) GO TO 1
IF (PROPAT.EQ.1.0) SC=3600.0
IF (PROPAT.EQ.2.0) SC=5915.0
IF (PROPAT.EQ.3.0) SC=7200.0
IF (PROPAT.EQ.4.0) SC=8910.0
IF (PROPAT.EQ.5.0) SC=5400.0
GO TO 2
1 CONTINUE
IF (PROPAT.EQ.1.0) SC=3950.0
IF (PROPAT.EQ.2.0) SC=6265.0
IF (PROPAT.EQ.3.0) SC=7585.0
IF (PROPAT.EQ.4.0) SC=9430.0
IF (PROPAT.EQ.5.0) SC=5500.0
2 CONTINUE
C INITIALIZE MINIMUM REQUIRED BLADE THICKNESS-TC-CHORD RATIO AT 3/4

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SUBROUTINE TDIST(C75K,TC75R,DIA,Z,AEDVAC)
SUBROUTINE: TDIST      DATE OF LAST REVISION: MAR 83
INPUT      OUTPUT      DEFINITION
C75R      C75R      CHORD LENGTH AT 3/4 RADIUS
TC75R      TC75R      (FEET)
DIA        DIA        SECTION THICKNESS-TO-
Z          Z          BLADE RATIO AT 3/4 RADIUS
AEDVAC     AEDVAC     PROPELLER DIAMETER (FEET)
              NO. OF PROPELLER BLADES
              EXPANDED AREA RATIO
              BLADE SECTION MAXIMUM
              THICKNESS ALONG PROPELLER
              RADIUS (FEET)
              REAL*4 TCOR,T1XR,T2OR,T3OR,T4OR,T5OR,T6OR,T7OR,T8OR,T9OR,
1            T1COR,RAT,C75R,TC75R,DIA,Z,AEDVAC,T75RWS
1            COMMON /THICKD/T0OR,T1XR,T2OR,T3OR,T4OR,T5OR,T6OR,T7OR,T8OR,T9OR,
1            T1COR,RAT
              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
              T75RWS=DIA*(0.0185-(0.00125*Z))
              CALCULATE RATIO OF MAXIMUM THICKNESSES AT 3/4 RADIUS
              KAT=T75R/T75RWS
              GENERATE A DISTRIBUTION OF BLADE SECTION MAXIMUM THICKNESSES ALONG
              THE PROPELLER RADIUS BASED ON THE RATIO CALCULATED ABOVE
              IF(.NOT.(Z.EQ.3.0))GO TO 1
              TCOR=0.0500*DIA
              T1XR=RAT*DIA*(0.05304-(0.0041*Z))
              GO TO 5
1 CONTINUE
              IF(.NOT.(Z.EQ.4.0))GO TO 2
              TCOR=0.045*DIA
              T1XR=RAT*DIA*(0.054046-(0.004165*Z))
              GO TO 5
2 CONTINUE

```

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 APP26760
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 APP27020
 APP27030
 APP27040
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 APP27060
 APP27070
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 APP27210
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APP27230
APP27240
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APP27330
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APP27350
APP27360
APP27370
APP27380
APP27390
APP27400
APP27410
APP27420
APP27430
APP27440
APP27450
APP27460

```

IF(.NOT.(2.EQ.5.0))GO TO 3
  TCCR=0.040*DIA
  TIXR=RAT*DIA*(0.054646-(0.004165*Z))
  GO TO 5
3 CONTINUE
  IF(.NOT.(2.EQ.6))GO TO 4
  TCCR=0.035*DIA
  TIXR=RAT*DIA*(0.054646-(0.004165*Z))
  GO TO 5
4 CONTINUE
  TCCR=0.035*DIA
  TIXR=RAT*DIA*(0.05384-(0.0041*Z))
  GO TO 5
5 CONTINUE
  T2OR=RAT*DIA*(0.0526-(0.0040*Z))
  T3OR=RAT*DIA*(0.0464-(0.0035*Z))
  T4OR=RAT*DIA*(0.0402-(0.0030*Z))
  T5OR=RAT*DIA*(0.0340-(0.0025*Z))
  T6OR=RAT*DIA*(0.0278-(0.0020*Z))
  T7OR=RAT*DIA*(0.0216-(0.0015*Z))
  T8OR=RAT*DIA*(0.0154-(0.0010*Z))
  T9OR=RAT*DIA*(0.0092-(0.0005*Z))
  T10OR=RAT*DIA*(0.0030-(0.0000*Z))
  RETURN
END

```



```

COMMON /CRDINT/CR
COMMON /VAL1/U1
COMMON /VAL2/U2
COMMON /VAL3/U3
COMMON /VAL4/U4
COMMON /VAL1/W1
COMMON /VAL2/W2
COMMON /VAL3/W3
COMMON /VAL4/W4
COMMON /A2HCMX/RIYVNA
COMMON /A2HCMY/RIXNA

DETERMINE BLADE SECTION MAXIMUM THICKNESS DISTRIBUTION

CALL TCIST(C75R,TC75R,CIA,Z,AEDVAC)

DETERMINE BLADE SECTION PROPERTIES

CALL BLCFRP

DETERMINE VOLUME OF A PROPELLER BLADE

CALL BLCLVCL(VOLBLD)

SPECIFY WEIGHT DENSITY OF MATERIAL SELECTED WHERE...
PRMAT      MATERIAL      WEIGHT DENSITY (LBF/IN**3)
  1      CAST IRON      .260
  2      CAST STEEL      .284
  3      TYPE 2 BRONZE    .305
  4      TYPE 4 NI-AL BRONZE .278
  5      STAINLESS STEEL .283

IF (PRMAT.EC.1) CIND=.260
IF (PRMAT.EC.2) CIND=.284
IF (PRMAT.EC.3) CIND=.305
IF (PRMAT.EC.4) CIND=.278
IF (PRMAT.EC.5) CIND=.283

CALCULATE PROPELLER BLADE WEIGHT

WEIGHT=VCLBLD*WC*(1728.0)
RETURN
END

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APP27570
APP27580
APP27590
APP27600
APP28010
APP28020
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APP28380
APP28390
APP28400

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APPENDIX C

ANALIZ CODES--DESIGN CASE NO. 1

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SUBROUTINE ANALIZ(ICALC)
INTEGER*4 ICALC
REAL*4 ETAO,WEIGHT,AEDVAG,DIA,N,PE,PDIVL,OS,TC75R,V,
1 RJCNU,RJCNU,R75RCL,R75RCU,AEAOCL,AEACCU,TC75CL,TC75CU,
2 FOMBAL,DIACNU,AEAOCL,TCSTRS,RJ,
3 VKITL,M1,Z,MAIR,MAINU,TEMP,NCSCRW,HCL,PATM,
4 PHATVA,PRMAT,DIALIM,ETARR,AEADHN,TC75MN,SC,
5 C75R,R75R,KT,KC,PD
COMMON /GLOECH/ETAO,WEIGHT,AEDVAG,DIA,N,PE,FDIVU,US,TC75R,V,RJCNU,
1 RJCNU,R75RCL,R75RCU,AEAOCL,AEACCU,TC75CL,TC75CU,PUMBAL,DIACNU,
2 AEACCU,TCSTRS,RJ
COMMON /PAR4/VK,TD,M1,Z,MAIR,MAINU,TEMP,NCSCRW,HCL,PATM,PHATVA,
1 PRMAT,DIALIM,ETARR,AEADHN,TC75MN,SC

THIS SUBROUTINE, COUPLED WITH CGPES/CONMIN, CONSTITUTES ANALYSIS
METHOD FOR "DESIGN CASE 1" PROPELLER SELECTION PROBLEMS

INPUT-INITIALIZATION PHASE

PII=3.14159264
IF(.NOT.(ICALC.EQ.1))GO TO 1

SET "DESIGN CASE 1" PARAMETERS

ENVIRONMENTAL
TEMP=55.0
WATRG=1.93E4
WATNU=.0000122850
PATM=14.7
PHATVA=.247

PROPELLER PARAMETERS
Z=5.0
PRGMAT=5.0

HULL PARAMETERS
WT=C.22
TC=C.15
ETARR=1.025
NCSCRW=1.0
HCL=19.0
DIALIM=22.0

SET DESIGN VARIABLES HELD FIXED FOR "DESIGN CASE 1"

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APP0C490
APP0C500
APP0C510
APP0C520
APP0C530
APP0C540
APP0C550
APP0C560
APP0C570
APP0C580
APP0C590
APP0C600
APP0C610
APP0C620
APP0C630
APP0C640
APP0C650
APP0C660
APP0C670
APP0C680
APP0C690
APP0C700
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APP0C730
APP0C740
APP0C750
APP0C760
APP0C770
APP0C780
APP0C790
APP0C800
APP0C810
APP0C820
APP0C830
APP0C840
APP0C850
APP0C860
APP0C870
APP0C880
APP0C890
APP0C900
APP0C910
APP0C920
APP0C930
APP0C940
APP0C950
APP0C960

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```

PE=181.53.0
VK=24.C
V=1.68E*VK
AECVAD=0.85
DIA=22.0
TC75R=((0.0185-U.C0125*Z)*Z)/(2.073*AECVAC)

END OF INPLT-INITIALIZATION PHASE

CC
CC
CC
C
C
C
GO TO 2
EXECUTION PHASE

1 CONTINUE
IF(.NOT.(ICALC.EQ.2))GO TO 2
CALL RNCAL(N)
CALL CF75RA(C75K)
CALL REY75R(C75R,R75R)
CALL CEFSA(RJ,KI,KQ)
CALL CFWEFF(RJ,KI,KQ,ETAD)
CALL CALCS(KC,QS)
CALL JCNA(RJ,RJCNL,RJCNJ)
CALL REYCN(K75R,R75RCL,R75RCU)
CALL EXTCN(Z,AEDVAD,TC75K,AEACCL,AEACCU,TC75CL,TC75CU)
CALL BLPOM(KI,PUWBAL)
CALL DIGNUA(DIACNU)
CALL CAVCNA(KI,AEADCV)
CALL STCNA(KC,C75K,TCSTRS)

END OF EXECUTION PHASE

CC
CC
CC
C
C
C
GO TO 2
2 CONTINUE
OUTPUT-RESULT PHASE

PD=(2.C*PI)*QS*N/33000.0
WRITE(6,9000)
WRITE(6,9001)
WRITE(6,9002) TEMP,WATRO,WAINU,PAIM,PAIVA
WRITE(6,9003) WT,TD,ETARR,NUSCAR,HCL,DIALIM
IF(.NOT.(PRCMAT.EQ.1.C))GO TO 81
WRITE(6,9005)SC
GO TO 86
CCCONTINUE
IF(.NOT.(PRCMAT.EQ.2.0))GO TO 82
WRITE(6,9006)SC

81

```

```

      82      GC TC E6
      CCNTINLE
      IF(.NOT.(PROMAT.EQ.3.0))GC TO E3
      WRITE(6,5007)SC

      83      GC TC E6
      CCNTINLE
      IF(.NOT.(PROMAT.EQ.4.0))GC TO E4
      WRITE(6,5008)SC

      84      GC TC E6
      CCNTINLE
      IF(.NOT.(PROMAT.EQ.5.0))GC TO E5
      WRITE(6,5009)SC

      85      GC TC E6
      CCNTINLE
      WRITE(6,9010)

      86      CCNTINLE
      WRITE(6,9011)PE,V,N,QS,PD,KJ,KT,KC,ETAC,K75R,DIA,PDIVD,
      1      AEDVAO,TC75R
      2      WRITE(6,9012)DIALIM,AEAMN,IC75MN
      3      CONTINLE
      RETURN

C      MISCELLANEOUS FORMAT STATEMENTS
C
9000  FORMAT(1X,'OPTIMIZATION RESULTS ----- DESIGN CASE NO. 1.0',
1      1X,'DESIGN VARIABLES SPECIFIED: SUBROUTINE "STRCNA",',
9001  FORMAT(1X,'ENVIRONMENTAL PARAMETERS: PE,V,AEDVAO,DIA,TC75R',
9002  FORMAT(1X,'FIC.4.0',
1      1X,'DENSITY (LBF-SEC/FT4)',12X,'= ',F10.4,'/',
2      1X,'25X',15X,'= ',E16.9,'/',F10.4,'/',
3      1X,'25X',17X,'= ',F10.4,'/',
4      1X,'25X',19X,'= ',F10.4,'/',
9003  FORMAT(1X,'FULL PARAMETERIZATION PRESSURE (PSIA)',21X,'= ',F10.4,'/',
1      1X,'25X',19X,'= ',F10.4,'/',
2      1X,'25X',19X,'= ',F10.4,'/',
3      1X,'25X',19X,'= ',F10.4,'/',
4      1X,'25X',19X,'= ',F10.4,'/',
9004  FORMAT(1X,'RELATIVE ROTATIONAL EFFICIENCY',14X,'= ',F10.4,'/',
1      1X,'25X',19X,'= ',F10.4,'/',
2      1X,'25X',19X,'= ',F10.4,'/',
3      1X,'25X',19X,'= ',F10.4,'/',
4      1X,'25X',19X,'= ',F10.4,'/',
9005  FORMAT(1X,'PROPELLER PARAMETERS: ',8X,'NUMBER OF BLADES',16X,'= ',
1      1X,'25X',19X,'= ',F10.4,'/',
2      1X,'25X',19X,'= ',F10.4,'/',
3      1X,'25X',19X,'= ',F10.4,'/',
4      1X,'25X',19X,'= ',F10.4,'/',
9006  FORMAT(1X,'MATERIAL TYPE',12X,'= ',CAST IRON,'/',
1      1X,'25X',19X,'= ',F10.4,'/',
2      1X,'25X',19X,'= ',F10.4,'/',
3      1X,'25X',19X,'= ',F10.4,'/',
4      1X,'25X',19X,'= ',F10.4,'/',
9007  FORMAT(1X,'MATERIAL TYPE',12X,'= ',BRONZE,'/',
1      1X,'25X',19X,'= ',F10.4,'/',
2      1X,'25X',19X,'= ',F10.4,'/',
3      1X,'25X',19X,'= ',F10.4,'/',
4      1X,'25X',19X,'= ',F10.4,'/',
9008  FORMAT(1X,'MATERIAL TYPE',12X,'= ',NIAL BRONZE,'/',
1      1X,'25X',19X,'= ',F10.4,'/',
2      1X,'25X',19X,'= ',F10.4,'/',
3      1X,'25X',19X,'= ',F10.4,'/',
4      1X,'25X',19X,'= ',F10.4,'/',

```



```

SUBROUTINE ANALZ(ICALC)
  INTEGER*4 ICALC
  REAL*4 EIAO,WEIGHT,AEDVAD,DIA,N,PE,FUIVL,QS,TC75R,V,
  1 RJCNU,RJCNU,R75ECL,R75RCL,AEAOCL,AEACCU,TC75CL,TC75CU,
  2 FUMBAL,DIACNU,AEACCU,TCSTRS,RJ,NCSCRW,HCL,PATM,
  3 VK,TC,WI,Z,WATRG,WATNU,TEMP,NCSCRW,HCL,PATM,SC,
  4 PWATVA,PROMAT,DIALIM,ETARR,AEADMN,TC75MN,SC,
  5 C75R,R75R,KT,KC,PD
  COMMON /GLOECM/ETAG,WEIGHT,AEDVAD,DIA,N,PE,FUIVL,QS,TC75R,V,RJCNU,
  1 RJCNU,R75ECL,R75RCL,AEAOCL,AEACCU,TC75CL,TC75CU,PWBAL,DIACNU,
  2 AEACCU,TCSTRS,RJ
  COMMON /FARM/VK,TD,WI,Z,WATRG,WATNU,TEMP,NCSCRW,HCL,PATM,PWATVA,
  1 PROMAT,DIALIM,ETARR,AEADMN,TC75MN,SC

  THIS SUBROUTINE, COUPLED WITH CUPE/CONMIN, CONSTITUTES ANALYSIS
  METHOD FOR *DESIGN CASE 1* PROPELLER SELECTION PROBLEMS

  INPT-INITIALIZATION PHASE

  PI1=3.14159264
  IF(.NOT.(ICALC.EQ.1))GO TO 1

  SET *DESIGN CASE 1* PARAMETERS

  ENVIRONMENTAL
    TEMP=51.0
    WATRO=1.9384
    WATNU=.000012850
    PATM=14.7
    PWATVA=.247

  PROPELLER PARAMETERS
    Z=5.0
    PROPMAT=5.0

  HULL PARAMETERS
    WT=C.24
    TC=C.14
    ETAPR=1.025
    NCSCRW=1.0
    HCL=19.0
    DIALIM=22.0

  SET DESIGN VARIABLES FELD FIXED FOR *DESIGN CASE 1*

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APP02170
 APP02180
 APP02190
 APP02200
 APP02210
 APP02220
 APP02230
 APP02240
 APP02250
 APP02260
 APP02270
 APP02280
 APP02290
 APP02300
 APP02310
 APP02320
 APP02330
 APP02340
 APP02350
 APP02360
 APP02370
 APP02380
 APP02390
 APP02400
 APP02410
 APP02420
 APP02430
 APP02440
 APP02450
 APP02460
 APP02470
 APP02480
 APP02490
 APP02500
 APP02510
 APP02520
 APP02530
 APP02540
 APP02550
 APP02560
 APP02570
 APP02580
 APP02590
 APP02600
 APP02610
 APP02620
 APP02630
 APP02640

```

PE=16153.0
VK=24.0
V=1.68E+VK
AECVAG=0.85
DIA=22.0
TC75R=((0.0185-0.00125*Z1)*Z1)/(2.075*AECVAG)

      END OF INPLT-INITIALIZATION PHASE

      GO TO 3

      EXECUTION PHASE

1 CONTINUE
  IF(.NOT.(ICALC.EQ.2))GC TO 2
    CALL RNCAL(N)
    CALL CF75RA(C75R)
    CALL REY75R(R75R)
    CALL CCEFSAR(J,R75R,KT,KQ)
    CALL CFWEFF(R,J,KT,KQ,ETAD)
    CALL CALCCS(KC,QSI)
    CALL JCNA(RJ,RJCNL,RJCNJ)
    CALL REYCNAR(R75R,R75RCL,R75RCU)
    CALL EXTCNAR(Z1,AECVAG,TC75R,AEACCL,AEAGCU,TC75CL,TC75CU)
    CALL BLPOW(IKI,POWBAL)
    CALL DICNUA(IDIACNL)
    CALL CAVCNA(KT,AEAGCU)
    CALL STRCNK(KC,KT,C75R,TCSTKS)

      END OF EXECUTION PHASE

      GO TO 2
2 CONTINUE

      OUTPUT-RESULT PHASE

      PG=(2.0*PII*QS*N)/33000.0
      WRITE(6,9000)
      WRITE(6,9001)
      WRITE(6,9002)TEMP,WATNU,WATNU,PATM,PWATVA
      WRITE(6,9003)WT,TD,ETARR,NUSCRW,HCL,DIALIM
      IF(.NOT.(PRCMAT.EQ.1.0))GO TO 81
      WRITE(6,9004)Z
      WRITE(6,9005)SC
      GC TO 86
      CC CONTINUE
      IF(.NOT.(PROMAT.EQ.2.0))GC TO 82
      WRITE(6,9006)SC

      81
  
```

APPG22650
 APPG22660
 APPG22670
 APPG22680
 APPG22690
 APPG22700
 APPG22710
 APPG22720
 APPG22730
 APPG22740
 APPG22750
 APPG22760
 APPG22770
 APPG22780
 APPG22790
 APPG22800
 APPG22810
 APPG22820
 APPG22830
 APPG22840
 APPG22850
 APPG22860
 APPG22870
 APPG22880
 APPG22890
 APPG22900
 APPG22910
 APPG22920
 APPG22930
 APPG22940
 APPG22950
 APPG22960
 APPG22970
 APPG22980
 APPG22990
 APPG23000
 APPG23010
 APPG23020
 APPG23030
 APPG23040
 APPG23050
 APPG23060
 APPG23070
 APPG23080
 APPG23090
 APPG23100
 APPG23110
 APPG23120

```

      GC TC 86
      CCNTINLE
      IF(.NOT.(PRCMAT.EQ.3.0))GO TO 83
      WRITE(6,5007)SC
      GC TC 86
      CCNTINLE
      IF(.NOT.(PRCMAT.EQ.4.0))GO TO 84
      WRITE(6,5008)SC
      GC TC 86
      CCNTINLE
      IF(.NOT.(PRCMAT.EQ.5.0))GO TO 85
      WRITE(6,5009)SC
      GC TC 86
      CCNTINLE
      WRITE(6,5010)
      CCNTINLE
      WRITE(6,9011)PE,V,N,US,PD,KJ,KT,KC,ETAC,R75R,DIA,PCIVD,
      AEDVAL,TCT5R
      1 WRITE(6,9012)DIALIM,AEQOMN,TC75MN
      3 CONTINUE
      RETURN
C
C MISCELLANEOUS FORMAT STATEMENTS
C
9000 FORMAT(1,'OPTIMIZATION RESULTS ----- DESIGN CASE NO. 1',/,
1 1X,'DESIGN VARIABLES SPECIFIED: PE,V,AEDVAL,DIA,TCT5R',/,
2 1X,'ENVIRONMENTAL PARAMETERS: TEMP (DEG F)',22X,'=',
3 1X,4,'/',
4 1X,25X,'DENSITY (LBF-SEC2/FT4)',12X,'=',F10.4,/,
5 1X,25X,'VISCOSITY (FT2/SEC)',15X,'=',E10.9,/,F10.4,/,
6 1X,25X,'ATMOSPHERIC PRESSURE (PSIA)',7X,'=',F10.4,/,
7 1X,25X,'WATER VAPORIZATION PRESSURE (PSIA)',7X,'=',F10.4,/,
8 1X,25X,'WAKE FRACTION',21X,'=',F10.4,/,
9 1X,25X,'FULL PARAMETERSTION FRACTION',21X,'=',F10.4,/,
10 1X,25X,'THRUST DEDUCTION EFFICIENCY',6X,'=',F10.4,/,
11 1X,25X,'RELATIVE ROTATIVE EFFICIENCY',6X,'=',F10.4,/,
12 1X,25X,'NUMBER OF PROPELLERS',14X,'=',F10.1,/,
13 1X,25X,'DEPTH TO SHAFT CENTERLINE (FT)',4X,'=',F10.4,/,
14 1X,25X,'DIAMETER LIMIT (FT)',15X,'=',F10.4,/,
15 1X,25X,'PROPELLER PARAMETERS:',8X,'NUMBER OF BLADES',18X,'=',
16 1X,10,/,
17 1X,25X,'MATERIAL TYPE',21X,'=',CAST IRCN,/,
18 1X,25X,'ALLOWABLE STRESS (PSI)',12X,'=',F10.1,/,
19 1X,25X,'MATERIAL TYPE',21X,'=',CAST STEEL,/,
20 1X,25X,'ALLOWABLE STRESS (PSI)',12X,'=',F10.1,/,
21 1X,25X,'MATERIAL TYPE',21X,'=',BRUNZE,/,
22 1X,25X,'ALLOWABLE STRESS (PSI)',12X,'=',F10.1,/,
23 1X,25X,'MATERIAL TYPE',21X,'=',NIAL BRUNZE,/,
24 1X,10,/)
  
```



```

SUBROUTINE ANALIZ(ICALC)
  INTEGER*4 ICALC
  REAL*4 ETAG,WEIGHT,AEDVAU,CIA,N,PE,FUIVC,QS,TC75R,V,
  1 RJCNL,RJCNL,R75RCL,R75RCL,R75RCL,AEACCL,AEACCU,TC75CL,TC75CU,
  2 FUIVC,DIA,CNU,AEACCU,TC75R,RJ,
  3 VK,TC,WT,Z,WATRC,WATNU,TEMP,NCS,CRW,HCL,PATM,
  4 PMATVA,PROMAT,DIALIM,ETARR,AEADMA,TC75MN,SC,
  5 C75R,R75R,KT,KC,PD
  COMMON /GLOECM/ETAG,WEIGHT,AEDVAU,DIA,N,PE,FUIVC,QS,TC75R,V,KJCNL,
  1 RJCNL,R75RCL,R75RCL,R75RCL,AEACCL,AEACCU,TC75CL,TC75CU,POMBAL,DIA,CNU,
  2 AEACCU,TC75R,RJ
  COMMON /PARAM/VK,TD,WT,Z,WATRO,WATNU,TEMP,NCS,CRW,HCL,PATM,PMATVA,
  1 PROMAT,DIALIM,ETARR,AEACMN,TC75MN,SC

  THIS SUBROUTINE, COUPLED WITH GCPES/CUNMIN, CONSTITUTES ANALYSIS
  METHOD FOR *DESIGN CASE 1* PROPELLER SELECTION PROBLEMS

  INPUT-INITIALIZATION PHASE

  PIJ=3.14159264
  IF(.NOT.(ICALC.EQ.1))GO TO 1

  SET *DESIGN CASE 1* PARAMETERS

  ENVIRONMENTAL
    TEMF=59.0
    WATRC=1.9384
    WATNU=.00001285
    PATP=14.7
    PMATVA=.247

  PROPELLER PARAMETERS
    Z=5.0
    PROCMAT=5.0

  HULL PARAMETERS
    W1=C.22
    TC=C.14
    ETARR=1.025
    NCS,CRW=1.0
    HCL=19.0
    DIALIM=22.0

  SET DESIGN VARIABLES HELD FIXED FOR *DESIGN CASE 1*

```



```

      83      GC IC
      CCAINLE
      IF(.NOT.(PRMAT.EQ.4.O))GC TO 84
      WRITE(6,9007)SC
      84      GC IC
      CCAINLE
      IF(.NOT.(PRMAT.EQ.5.C))GC TO 85
      WRITE(6,9008)SC
      85      GC IC
      CCAINLE
      WRITE(6,9010)
      86      CCAINLE
      WRITE(6,9011)PE,V,N,QS,PD,K,J,KT,KC,ETAC,R75R,DIA,PCIVD,
      AEDVAC,TC75R
      1      WRITE(6,9012)DIALIM,AEADMN,IC75MN
      3      CONTINUE
      RETURN
C
C      MISCELLANEOUS FORMAT STATEMENTS
C
9000  FORMAT(1X,'OPTIMIZATION RESULTS ----- DESIGN CASE NO. 1.1./
1X,'DESIGN VARIABLES SPECIFIED: PE,V./)
9001  FORMAT(1X,'ENVIRONMENTAL PARAMETERS: TEMP (DEG F),22X,==',
1X,4./)
1X,25X,'DENSITY (LBF-SEC2/FT4), 12X,==',F10.4,/,
1X,25X,'VISCOSITY (FT2/SEC), 15X,==',E16.9,/,
1X,25X,'ATMOSPHERIC PRESSURE (PSIA), 7X,==',F10.4,/,
1X,25X,'WATER VAPORIZATION PRESSURE (PSIA), 7X,==',F10.4,/,
9003  FORMAT(1X,'FULL THRUST REDUCTION FACTOR, 13X,'WAKE FRACTION, 21X,==',F10.4,/,
1X,25X,'THRUST REDUCTION EFFICIENCY, 9X,==',F10.4,/,
1X,25X,'RELATIVE CF PROPELLERS, 14X,==',F10.4,/,
1X,25X,'NUMBER OF SHAFT CENTERLINE (FT), 15X,==',F10.4,/,
1X,25X,'DEPTH TO SHAFT CENTERLINE (FT), 15X,==',F10.4,/,
9004  FORMAT(1X,'PROPELLER PARAMETERS: 8X,'NUMBER OF BLADES',18X,==',
1X,10./)
9005  FORMAT(1X,25X,'MATERIAL TYPE, 21X,==',CAST IRON,/,
1X,25X,'ALL CABLE STRESS (PSI), 12X,==',F10.1,/,
9006  FORMAT(1X,25X,'MATERIAL TYPE, 21X,==',CAST STEEL,/,
1X,25X,'ALL CABLE STRESS (PSI), 12X,==',F10.1,/,
9007  FORMAT(1X,25X,'MATERIAL TYPE, 21X,==',BRONZE,/,
1X,25X,'ALL CABLE STRESS (PSI), 12X,==',F10.1,/,
9008  FORMAT(1X,25X,'MATERIAL TYPE, 21X,==',N-AL BRONZE,/,
1X,25X,'ALL CABLE STRESS (PSI), 12X,==',F10.1,/,
9009  FORMAT(1X,25X,'MATERIAL TYPE, 21X,==',STAINLESS STEEL,/,
1X,25X,'ALL CABLE STRESS (PSI), 12X,==',F10.1,/)

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APP04330
APP04340
APP04350
APP04360
APP04370
APP04380
APP04390
APP04400
APP04410
APP04420
APP04430
APP04440
APP04450
APP04460
APP04470
APP04480
APP04490
APP04500
APP04510
APP04520
APP04530
APP04540
APP04550
APP04560
APP04570
APP04580
APP04590
APP04600
APP04610
APP04620
APP04630
APP04640
APP04650
APP04660
APP04670
APP04680
APP04690
APP04700
APP04710
APP04720
APP04730
APP04740
APP04750
APP04760
APP04770
APP04780
APP04790
APP04800

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901C FORMAT(1X,2SX,MATERIAL TYPE,21X,.,=, NCT CONSIDERED,/,/),
9011 FORMAT(1X,2SX,SELECTION VALUES,12X,.,PE (HP),27X,.,=,F10.1,/,
1X,2SX,V (FT/SEC),23X,.,=,F10.4,/,
1X,2SX,A (RPM),23X,.,=,F10.4,/,
1X,2SX,C S (FT-LBF),23X,.,=,F10.2,/,
1X,2SX,PD (HP),23X,.,=,F10.4,/,
1X,2SX,J T,23X,.,=,F10.4,/,
1X,2SX,KQ,23X,.,=,F10.4,/,
1X,2SX,EIAQ,23X,.,=,E10.1,/,
1X,2SX,REV 75R,23X,.,=,F10.4,/,
1X,2SX,DIA (FT),23X,.,=,F10.4,/,
1X,2SX,PD,23X,.,=,F10.4,/,
1X,2SX,AE/AC,23X,.,=,F10.4,/,
1X,2SX,T/C,23X,.,=,F10.4,/,
9012 FORMAT(1X,2SX,CONSTRAINT VALUES,11X,MAX DIA (FT),22X,.,=,F10.4,/,
1X,2SX,MIN AE/AC,25X,.,=,F10.4,/,
1X,2SX,MIN T/C,25X,.,=,F10.6),
2 END

```

```

APPC4610
APPC4620
APPC4630
APPC4640
APPC4650
APPC4660
APPC4670
APPC4680
APPC4690
APPC4700
APPC4710
APPC4720
APPC4730
APPC4740
APPC4750
APPC4760
APPC4770
APPC4780
APPC4790
APPC4800
APPC4810
APPC4820
APPC4830
APPC4840
APPC4850
APPC4860
APPC4870
APPC4880
APPC4890
APPC4900
APPC4910
APPC4920
APPC4930
APPC4940
APPC4950
APPC4960
APPC4970
APPC4980
APPC4990

```

```

SUBROUTINE ANALIZ(ICALC)
  INTEGER*4 I,ICALC
  REAL*4 ETAD,WEIGHT,AEDVAD,DIA,N,PE,PDIVD,QS,TC75R,V,
1  FJCNL,RJCNL,R75ECL,R75RCL,AEACCL,AEACCU,TC75CL,TC75CU,
2  FJCNL,DIA,AEACCU,AEACCU,TC75R,RJ,
3  FJCNL,DIA,AEACCU,AEACCU,TC75R,RJ,
4  FJCNL,DIA,AEACCU,AEACCU,TC75R,RJ,
5  FJCNL,DIA,AEACCU,AEACCU,TC75R,RJ,
  COMMON /R75RCL,R75RCL,AEACCU,AEACCU,TC75R,RJ,
1  RJCNL,R75RCL,R75RCL,AEACCU,AEACCU,TC75R,RJ,
2  AEACCU,TC75R,RJ,
  COMMON /PARAM/VK,TC,WI,Z,WATRU,WATNU,TEMP,NLSCRW,HCL,PATM,PWATVA,
1  PRCHAT,LIALIM,ETARR,AEACMN,TC75MN,SC
  THIS SUBROUTINE COUPLED WITH LOPES/CONMIN, CONSTITUTES ANALYSIS
  METHOD FOR DESIGN CASE 1" PROPELLER SELECTION PROBLEMS
  INPUT-INITIALIZATION PHASE
  PI=3.14159264
  IF(.NOT.(ICALC.EQ.1))GO TO 1
  SET *DESIGN CASE 1" PARAMETERS
  ENVIRONMENTAL
  TEMP=55.0
  WATRU=1.9384
  WATNU=.00012265
  PATM=14.7
  PWATVA=.247
  PROPELLER PARAMETERS
  Z=5.0
  PRCHAT=5.0
  HULL PARAMETERS
  WT=C.22
  TC=C.12
  ETARR=1.025
  NLSCRW=1.0
  HCL=19.0
  LIALIM=22.0
  SET DESIGN VARIABLES HELD FIXED FOR *DESIGN CASE 1"

```

```

APP05020
APP05030
APP05040
APP05050
APP05060
APP05070
APP05080
APP05090
APP05100
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

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APPENDIX D

CONTROL CARD IMAGES--DESIGN CASE NO. 1

\$A	TITLE	E-SERIES	PROPELLER	OPTIMIZATION	IPDBG
\$B	WAGENINGEN	NDV	NSV	N2VAR	NACMX1
\$C	NCALC	ITPMX	ICWDIR	NSCAL	15
\$D1	IPRINT	ICOO	CT	CTMIN	THEIA
\$D2	FUCH	FOCHM	ALPFX	ABGBJI	
\$E	C.0V01	C.0C01	SGNCPT		
\$F	CELFUN	ICBJ	1.0	SCAL	
\$G	NDVTOT	VLB	0.1	1.0	
\$H	VLB	1.8	0.5	1.0	
\$I1	0.01	1.4	AMULT		
\$I2	0.4	23	1.0		
\$J1	NDSSGN	7			
\$J2	1				
\$J3	2				
\$J4	3				
\$J5	4				
\$J6	5				
\$J7	6				
\$J8	7				
\$J9	8				
\$J10	9				
\$J11	10				
\$J12	11				
\$J13	12				
\$J14	13				
\$J15	14				
\$J16	15				
\$J17	16				
\$J18	17				
\$J19	18				
\$J20	19				
\$J21	20				
\$J22	21				
\$J23	22				
\$J24	23				
\$J25	24				
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\$J253	252				
\$J254	253				
\$J255	254				
\$J256	255				
\$J257	256				
\$J258	257				

\$A	TITLE	E-SERIES	PROPELLER	OPTIMIZATION	AXAPRX	IPNPUT	IPUUG
\$B	WAGENINGEN	NDV	NSV	N2VAR	ITRM	LINCBJ	NACMX1
\$C	IPRINT	ITMAX	ICNDR	NSCAL	CTL	CTLMIN	THETA
\$D1	FDCH	ICOO	CT	CTMIN			
\$D2	0.0001	C.0001	ALPHAX	ABCBJI			
\$E	ADVTGT	ICBJ	SENCFT				
\$F	VLE	VUB	1.0 X	SCAL			
	0.2	1.1	0.30	1.0			
	1.0	50.0	30.0	10.0			
	0.01	1.6	0.1	1.0			
	0.4	1.4	0.5	1.0			
\$G	0.003	C.5	0.0300	0.010			
	ADSSGN	IDSGN	AMULT				
	1	3	1.0				
	2	4	1.0				
	3	23	1.0				
	4	7	1.0				
	5	9	1.0				
\$H	NCON	JCON	LCCN	SCAL2			
\$I1	ICCN	SCAL1	BU				
\$I2	1	1	0.0	1.0			
-1.0	+12	1.12	0.0	1.0			
-1.0	+13	1.13	0.0	1.0			
-1.0	+14	1.14	0.0	1.0			
-1.0	+15	1.15	0.0	1.0			
-1.0	+16	1.16	0.0	1.0			
-1.0	+17	1.17	0.0	1.0			
-1.0	+18	1.18	0.0	1.0			
-1.0	+19	1.19	0.0	1.0			
-1.0	+20	1.20	0.0	1.0			
-1.0	+16	1.0	0.0	1.0			

-1.0	21	0.0	1.0
-1.0	+16	0.0	1.0
\$V	22	0.0	1.0
END	+16		

CONTROL PROGRAM
FOR
ENGINEERING SYNTHESES

HAGENINCA B-SERIES PROPELLER OPTIMIZATION

74477

IMAGE

74477

IMAGE

[illegible]

• • ESTIMATED DATA SIMULTANEOUS

[illegible]

237


```

.....
C L P M I N
.....
FORTHAN PROGRAM FOR
.....
CONSTRAINT FUNCTION MINIMIZATION
.....

```

```

INITIAL FUNCTION INFORMATION
CBJ = -C.152694E+00
CELSICA VARIABLES IX-VELUM
C.1E000E+00 0.50000E+00
CONSTRAINT VALUES
C-VECTURE
-0.32289E+01 -0.23188E+00 -0.23188E+00 -0.76485E+03 -0.40100E+00 -0.20000E+00

```

```

FINAL OPTIMIZATION INFORMATION
OBJ = -0.719073E+00
DECISION VARIABLES IN VECTOR
C.73112E+00 0.10032E+01
CONSTRAINT VALUES IN VECTOR
11 -0.3160E-01 -0.3338E+00 -0.3239E+02 -0.96660E+03 -0.40000E+00 -0.20000E+00
0.1321E-01
THERE ARE 0 VIOLATED CONSTRAINTS
CONSTRAINT NUMBERS ARE
THERE ARE 0 ACTIVE SIDE CONSTRAINTS
TERMINATION CRITERION
ABS(C-11)-110.1111 LESS THAN DELFUN FOR 3 ITERATIONS
ABS(C-11)-0.1111 LESS THAN DELFUN FOR 3 ITERATIONS
NUMBER OF ITERATIONS = 14
OBJECTIVE FUNCTION WAS EVALUATED 69 TIMES
CONSTRAINT FUNCTIONS WERE EVALUATED 69 TIMES

```

240

```
CALL CASE (AGE, NU, I  
CALL LINE = STR(LNA=
```

37

0-6000
1-9999
2-9999
3-9999
4-9999

2

[illegible]

2

0-0045
540-5
JAN 23 1971
JAN 23 1971

••
42

14:31:51.34
15:06:37
16:09:37
17:41:51.0
18:21:22.0

451-7/1
1197/20
1196/1

5:

992120
PC354.3
M364

PROGRAM CALLS TO ANALYZE
SCALE CALLS
10
2

IMAGET

1247

[illegible]

246

```
INITIAL FUNCTION INFORMATION
OBJ = -6.15264E+0C
DESIGN VARS=5 IN-VARIABLES
CONSTRAINT VALUES=10-VECTORS
CONSTRAINT VALUES=-0.97833E+00 -0.22222E+00 -0.33333E+00 -0.33333E+00 -0.33333E+00 -0.76406E+0J -0.40000E+0J -0.20000E+00
```

248

```

OPTIMIZATION RESULTS
OBJECTIVE FUNCTION 1    FUNCTION VALUE 6.7097E+00
GLOBAL RELATION
DESIGN VARIABLES
  ID  C.V.  GLOBAL  LOWER  VALUE  UPPER
      V1    NL    BOUND  BOUND  BOUND
      1    1    0.1000E+00  0.1000E+00  0.1000E+01
      2    2    0.1000E+00  0.1000E+00  0.1000E+01
DESIGN CONSTRAINTS
  ID  GLOBAL  LOWER  UPPER
      V1    NL    BOUND  BOUND
      1    1    0.1000E+00  0.1000E+01
      2    2    0.1000E+00  0.1000E+01
      3    3    0.1000E+00  0.1000E+01
      4    4    0.1000E+00  0.1000E+01
      5    5    0.1000E+00  0.1000E+01
      6    6    0.1000E+00  0.1000E+01
      7    7    0.1000E+00  0.1000E+01
      8    8    0.1000E+00  0.1000E+01
      9    9    0.1000E+00  0.1000E+01
      10   10   0.1000E+00  0.1000E+01
      11   11   0.1000E+00  0.1000E+01
      12   12   0.1000E+00  0.1000E+01
      13   13   0.1000E+00  0.1000E+01
      14   14   0.1000E+00  0.1000E+01
      15   15   0.1000E+00  0.1000E+01
      16   16   0.1000E+00  0.1000E+01
      17   17   0.1000E+00  0.1000E+01
      18   18   0.1000E+00  0.1000E+01
      19   19   0.1000E+00  0.1000E+01
      20   20   0.1000E+00  0.1000E+01
      21   21   0.1000E+00  0.1000E+01
      22   22   0.1000E+00  0.1000E+01
      23   23   0.1000E+00  0.1000E+01
      24   24   0.1000E+00  0.1000E+01
      25   25   0.1000E+00  0.1000E+01
      26   26   0.1000E+00  0.1000E+01
      27   27   0.1000E+00  0.1000E+01
      28   28   0.1000E+00  0.1000E+01
      29   29   0.1000E+00  0.1000E+01
      30   30   0.1000E+00  0.1000E+01
      31   31   0.1000E+00  0.1000E+01
      32   32   0.1000E+00  0.1000E+01
      33   33   0.1000E+00  0.1000E+01
      34   34   0.1000E+00  0.1000E+01
      35   35   0.1000E+00  0.1000E+01
      36   36   0.1000E+00  0.1000E+01
      37   37   0.1000E+00  0.1000E+01
      38   38   0.1000E+00  0.1000E+01
      39   39   0.1000E+00  0.1000E+01
      40   40   0.1000E+00  0.1000E+01
      41   41   0.1000E+00  0.1000E+01
      42   42   0.1000E+00  0.1000E+01
      43   43   0.1000E+00  0.1000E+01
      44   44   0.1000E+00  0.1000E+01
      45   45   0.1000E+00  0.1000E+01
      46   46   0.1000E+00  0.1000E+01
      47   47   0.1000E+00  0.1000E+01
      48   48   0.1000E+00  0.1000E+01
      49   49   0.1000E+00  0.1000E+01
      50   50   0.1000E+00  0.1000E+01
      51   51   0.1000E+00  0.1000E+01
      52   52   0.1000E+00  0.1000E+01
      53   53   0.1000E+00  0.1000E+01
      54   54   0.1000E+00  0.1000E+01
      55   55   0.1000E+00  0.1000E+01
      56   56   0.1000E+00  0.1000E+01
      57   57   0.1000E+00  0.1000E+01
      58   58   0.1000E+00  0.1000E+01
      59   59   0.1000E+00  0.1000E+01
      60   60   0.1000E+00  0.1000E+01
      61   61   0.1000E+00  0.1000E+01
      62   62   0.1000E+00  0.1000E+01
      63   63   0.1000E+00  0.1000E+01
      64   64   0.1000E+00  0.1000E+01
      65   65   0.1000E+00  0.1000E+01
      66   66   0.1000E+00  0.1000E+01
      67   67   0.1000E+00  0.1000E+01
      68   68   0.1000E+00  0.1000E+01
      69   69   0.1000E+00  0.1000E+01
      70   70   0.1000E+00  0.1000E+01
      71   71   0.1000E+00  0.1000E+01
      72   72   0.1000E+00  0.1000E+01
      73   73   0.1000E+00  0.1000E+01
      74   74   0.1000E+00  0.1000E+01
      75   75   0.1000E+00  0.1000E+01
      76   76   0.1000E+00  0.1000E+01
      77   77   0.1000E+00  0.1000E+01
      78   78   0.1000E+00  0.1000E+01
      79   79   0.1000E+00  0.1000E+01
      80   80   0.1000E+00  0.1000E+01
      81   81   0.1000E+00  0.1000E+01
      82   82   0.1000E+00  0.1000E+01
      83   83   0.1000E+00  0.1000E+01
      84   84   0.1000E+00  0.1000E+01
      85   85   0.1000E+00  0.1000E+01
      86   86   0.1000E+00  0.1000E+01
      87   87   0.1000E+00  0.1000E+01
      88   88   0.1000E+00  0.1000E+01
      89   89   0.1000E+00  0.1000E+01
      90   90   0.1000E+00  0.1000E+01
      91   91   0.1000E+00  0.1000E+01
      92   92   0.1000E+00  0.1000E+01
      93   93   0.1000E+00  0.1000E+01
      94   94   0.1000E+00  0.1000E+01
      95   95   0.1000E+00  0.1000E+01
      96   96   0.1000E+00  0.1000E+01
      97   97   0.1000E+00  0.1000E+01
      98   98   0.1000E+00  0.1000E+01
      99   99   0.1000E+00  0.1000E+01
      100  100  0.1000E+00  0.1000E+01
  
```

[illegible]

MURRAY CALLS TO ANALYZE
SCALE CALLS
1 2 3

CARD	IMAGE
1	
2	
3	
4	
5	
6	

94	TITLE	B-SERIES	PROPELLER	OPTIMIZATION	MAXPRX	IPNPLT	IPUBG
95	ACALC	NDV	MSV	M2VAR	ITEM	LINDEJ	NALM3
96	IFRIN	ITRAX	ICPDR	NSCAL	LTL	CILM3	THE1A
97	FOCM	FOCM	CT	CTRM			
98	FOCM	FOCM	ALFAX	ABOBJI			
99	DELUM	DELUM					
9A	MCVOT	ICBJ	SCAPTI				
9B	VLENQ	VLENQ	1.0	SCAL			
9C	FOCM	5.0	5.0	1.0			
9D	FOCM	1.0	1.0	1.0			
9E	MCVOT	1.0	0.0	0.0			
9F	ACOUN	2.0	1.0	0.0			
9G	ICOM	1.0	1.0	1.0			
9H	SCAL	1.0	1.0	1.0			
9I	ICOM	1.0	1.0	1.0			
9J	SCAL	1.0	1.0	1.0			
9K	ICOM	1.0	1.0	1.0			
9L	SCAL	1.0	1.0	1.0			
9M	ICOM	1.0	1.0	1.0			
9N	SCAL	1.0	1.0	1.0			
9O	ICOM	1.0	1.0	1.0			
9P	SCAL	1.0	1.0	1.0			
9Q	ICOM	1.0	1.0	1.0			
9R	SCAL	1.0	1.0	1.0			
9S	ICOM	1.0	1.0	1.0			
9T	SCAL	1.0	1.0	1.0			
9U	ICOM	1.0	1.0	1.0			
9V	SCAL	1.0	1.0	1.0			
9W	ICOM	1.0	1.0	1.0			
9X	SCAL	1.0	1.0	1.0			
9Y	ICOM	1.0	1.0	1.0			
9Z	SCAL	1.0	1.0	1.0			

[illegible]

	CALCULATION CONTROL, ALAR
	PEAKING ANALYSIS
1	SINGLE ANALYSA
2	SEMI-AUTOMATIC FUNCTIONAL SPACE
3	FULLY AUTOMATIC OPTIMIZATION
4	FUNCTIONAL SPACE OPTIMIZATION
5	OPTIMIZATION
6	OPTIMIZATION

```
GLOBAL VARIABLE NUMBER OF OBJECTIVE
MULTIPLIER (NEGATIVE INDICATES MINIMIZATION) = 0.1000E+01
COLUMN PARAMETERS (IF ZERO, COLUMN IN DEFAULT WILL OVER-RIDE)
      1      2      3      4      5      6      7      8      9      10
      11     12     13     14     15     16     17     18     19     20
      21     22     23     24     25     26     27     28     29     30
      31     32     33     34     35     36     37     38     39     40
      41     42     43     44     45     46     47     48     49     50
      51     52     53     54     55     56     57     58     59     60
      61     62     63     64     65     66     67     68     69     70
      71     72     73     74     75     76     77     78     79     80
      81     82     83     84     85     86     87     88     89     90
      91     92     93     94     95     96     97     98     99     100
      101    102    103    104    105    106    107    108    109    110
      111    112    113    114    115    116    117    118    119    120
      121    122    123    124    125    126    127    128    129    130
      131    132    133    134    135    136    137    138    139    140
      141    142    143    144    145    146    147    148    149    150
      151    152    153    154    155    156    157    158    159    160
      161    162    163    164    165    166    167    168    169    170
      171    172    173    174    175    176    177    178    179    180
      181    182    183    184    185    186    187    188    189    190
      191    192    193    194    195    196    197    198    199    200
      201    202    203    204    205    206    207    208    209    210
      211    212    213    214    215    216    217    218    219    220
      221    222    223    224    225    226    227    228    229    230
      231    232    233    234    235    236    237    238    239    240
      241    242    243    244    245    246    247    248    249    250
      251    252    253    254    255    256    257    258    259    260
      261    262    263    264    265    266    267    268    269    270
      271    272    273    274    275    276    277    278    279    280
      281    282    283    284    285    286    287    288    289    290
      291    292    293    294    295    296    297    298    299    300
      301    302    303    304    305    306    307    308    309    310
      311    312    313    314    315    316    317    318    319    320
      321    322    323    324    325    326    327    328    329    330
      331    332    333    334    335    336    337    338    339    340
      341    342    343    344    345    346    347    348    349    350
      351    352    353    354    355    356    357    358    359    360
      361    362    363    364    365    366    367    368    369    370
      371    372    373    374    375    376    377    378    379    380
      381    382    383    384    385    386    387    388    389    390
      391    392    393    394    395    396    397    398    399    400
      401    402    403    404    405    406    407    408    409    410
      411    412    413    414    415    416    417    418    419    420
      421    422    423    424    425    426    427    428    429    430
      431    432    433    434    435    436    437    438    439    440
      441    442    443    444    445    446    447    448    449    450
      451    452    453    454    455    456    457    458    459    460
      461    462    463    464    465    466    467    468    469    470
      471    472    473    474    475    476    477    478    479    480
      481    482    483    484    485    486    487    488    489    490
      491    492    493    494    495    496    497    498    499    500
      501    502    503    504    505    506    507    508    509    510
      511    512    513    514    515    516    517    518    519    520
      521    522    523    524    525    526    527    528    529    530
      531    532    533    534    535    536    537    538    539    540
      541    542    543    544    545    546    547    548    549    550
      551    552    553    554    555    556    557    558    559    560
      561    562    563    564    565    566    567    568    569    570
      571    572    573    574    575    576    577    578    579    580
      581    582    583    584    585    586    587    588    589    590
      591    592    593    594    595    596    597    598    599    600
      601    602    603    604    605    606    607    608    609    610
      611    612    613    614    615    616    617    618    619    620
      621    622    623    624    625    626    627    628    629    630
      631    632    633    634    635    636    637    638    639    640
      641    642    643    644    645    646    647    648    649    650
      651    652    653    654    655    656    657    658    659    660
      661    662    663    664    665    666    667    668    669    670
      671    672    673    674    675    676    677    678    679    680
      681    682    683    684    685    686    687    688    689    690
      691    692    693    694    695    696    697    698    699    700
      701    702    703    704    705    706    707    708    709    710
      711    712    713    714    715    716    717    718    719    720
      721    722    723    724    725    726    727    728    729    730
      731    732    733    734    735    736    737    738    739    740
      741    742    743    744    745    746    747    748    749    750
      751    752    753    754    755    756    757    758    759    760
      761    762    763    764    765    766    767    768    769    770
      771    772    773    774    775    776    777    778    779    780
      781    782    783    784    785    786    787    788    789    790
      791    792    793    794    795    796    797    798    799    800
      801    802    803    804    805    806    807    808    809    810
      811    812    813    814    8
```

FOLIN	FUCHS	CT	CTMIN
0.1000E-02	0.1000E-02	0.0	0.0
CTA	CTMIN	META	PW
0.0	0.0	0.0	0.0
DELUN	DARUN	ALPHAX	ABSCJA
0.0	0.0	0.0	0.0

[illegible][illegible][illegible]

TOTAL ALPHEP UP CONSUMED PARALLELS * 14

• • ESTIMATED DATA STORAGE REQUIREMENTS

INPUT EXEC	MAXIMUM AVAILABLE	INPUT EXECUTION	UNILVER AVAILABLE
84	10000	12	1000

DESIGN VARIABLES SPECIFIED:
ENVIRONMENTAL PARAMETERS:

PE-4
TEMP DEG F -55.0000
DENSITY LB/IN³ 1.2984
VAPOR PRESSURE PSIA 0.120000
WATER VAPORIZATION PRESSURE PSIA 6.2470
= 55.0000
= 0.120000
= 6.2470

MAKE FRACTION REDUCTIONS EFFICIENT

• • • • •

NUMERICAL TYPE
MATERIAL TYPE
ALLOWABLE STRESS (PSI)

== STAINLESS STEEL

PE
V
N
Q
D

1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53 54 55 56 57 58 59 60 61 62 63 64 65 66 67 68 69 70 71 72 73 74 75 76 77 78 79 80 81 82 83 84 85 86 87 88 89 90 91 92 93 94 95 96 97 98 99 100

	MAX	MIM	MIM	CL A (FY)
				AC
				T/C .75R

25457.0
5191.3
6000.0

[illegible]

```

FINAL OPTIMIZATION INFORMATION
OBJ = -C.71085E+00
DECISIVE VARIABLES (X-VECTOR)
11 C.8204E+30 0.2199E+02 0.7443E+00 0.9901E+00 0.3300E-01
CONSTRAINT VALUES (G-VECTOR)
11 -C.4109E+00 -0.3110E+00 -0.3001E+02 -0.3001E+02 -0.3001E+02 -0.3001E+02 -0.3001E+02 -0.3001E+02 -0.3001E+02 -0.3001E+02 -0.3001E+02 -0.3001E+02
THERE ARE 2 ACTIVE CONSTRAINTS
CONSTRAINT NUMBERS ARE
9
10
THERE ARE 0 VIOLATED CONSTRAINTS
THERE ARE 0 ACTIVE SIDE CONSTRAINTS
TERMINATION CRITERION
ASSIGN(J1)-OBJ(J1) LESS THAN DAFUN FOR 30 ITERATIONS
NUMBER OF ITERATIONS = 83
CONJECTIVE FUNCTION WAS EVALUATED 548 TIMES
CONSTRAINT FUNCTIONS WERE EVALUATED 548 TIMES

```

259

DESIGN VARIABLES SPECIFIED:
ENVIRONMENTAL PARAMETERS:

[illegible][illegible]

NUMBER OF BLADES	WATERMATERIAL TYPE	STRESS (PSI)
5.0	STAINLESS	5400.0
5.0	STEEL	

[illegible]

MAX	CL A (F T)	22.0000
MIN	AE/AO	6.5269
MIN	Y/C	0.021998

PROGRAM CALLS TO ANALYZE
ICALL CALLS
1 542

CCCCC UUUUU PPPPP EEEEE SSSSS
 CCCCC UUUUU PPPPP EEEEE SSSSS
 CCCCC UUUUU PPPPP EEEEE SSSSS
 CCCCC UUUUU PPPPP EEEEE SSSSS

CENTRAL PROGRAM
 FOR
 ENGINEERING SYNTHESIS

TITLE
 MAGENICA B-SERIES PROPELLER OPTIMIZATION

LANE	IMAGE
1	100 bp DNA ladder
2	100 bp DNA ladder
3	100 bp DNA ladder
4	100 bp DNA ladder
5	100 bp DNA ladder
6	100 bp DNA ladder
7	100 bp DNA ladder
8	100 bp DNA ladder
9	100 bp DNA ladder
10	100 bp DNA ladder
11	100 bp DNA ladder
12	100 bp DNA ladder
13	100 bp DNA ladder
14	100 bp DNA ladder
15	100 bp DNA ladder
16	100 bp DNA ladder
17	100 bp DNA ladder
18	100 bp DNA ladder
19	100 bp DNA ladder
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21	100 bp DNA ladder
22	100 bp DNA ladder
23	100 bp DNA ladder
24	100 bp DNA ladder
25	100 bp DNA ladder
26	100 bp DNA ladder
27	100 bp DNA ladder
28	100 bp DNA ladder
29	100 bp DNA ladder
30	100 bp DNA ladder
31	100 bp DNA ladder
32	100 bp DNA ladder
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34	100 bp DNA ladder
35	100 bp DNA ladder
36	100 bp DNA ladder
37	100 bp DNA ladder
38	100 bp DNA ladder
39	100 bp DNA ladder
40	100 bp DNA ladder
41	100 bp DNA ladder
42	100 bp DNA ladder
43	100 bp DNA ladder
44	100 bp DNA ladder
45	100 bp DNA ladder
46	100 bp DNA ladder
47	100 bp DNA ladder
48	100 bp DNA ladder
49	100 bp DNA ladder
50	100 bp DNA ladder
51	100 bp DNA ladder
52	100 bp DNA ladder
53	100 bp DNA ladder
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55	100 bp DNA ladder
56	100 bp DNA ladder
57	100 bp DNA ladder
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89	100 bp DNA ladder
90	100 bp DNA ladder
91	100 bp DNA ladder
92	100 bp DNA ladder
93	100 bp DNA ladder
94	100 bp DNA ladder
95	100 bp DNA ladder
96	100 bp DNA ladder
97	100 bp DNA ladder
98	100 bp DNA ladder
99	100 bp DNA ladder
100	100 bp DNA ladder

14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86	87	88	89	90	91	92	93	94	95	96	97	98	99	100			
11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86	87	88	89	90	91	92	93	94	95	96	97	98	99	100
11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86	87	88	89	90	91	92	93	94	95	96	97	98	99	100
11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86	87	88	89	90	91	92	93	94	95	96	97	98	99	100
11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86	87	88	89	90	91	92	93	94	95	96	97	98	99	100
11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69																															

TOTAL ALPHEP OF UNSHOWNED PARAPLENS * 14

• • ESTIPATED DATA STORAGE RECLIFEMENTS

REAL	INTEGER
INPUT EXECUTION	INPUT EXECUTION
AVAILABLE	AVAILABLE
10000	1000

266

```

.....
C C P M J N
.....
FORTRAN PROGRAM FOR
.....
CONSTRAINED FUNCTION MINIMIZATION
.....

```

INITIAL FUNCTION INFORMATION

```

OBJ = -C.166409E+00
DECISION VARIABLES (N-VECTOR)
11 C.38000E+00 0.30000E+02 0.10000E+00 0.50000E+00 C.30000E-01
CONSTRAINT VALUES (M-VECTOR)
11 -C.13300E-01 -0.23124E+00 -0.10017E+03 0.36324E+00 C.15000E+00 -0.15000E+00 0.56102E+01

```

```

FINAL OPTIMIZATION INFORMATION
OBJ = -C.705752E+00
DECSICA VARIABLES (N-VECTOR)
  C.01400E+00 0.21968E+02 0.73932E+00 C.10071E+01 C.04152E-04
CONSTRAINT VALUES (N-VECTOR)
  -C.54210E+00 -0.51751E+00 0.17331E-02 -0.71301E+03 -0.39388E+00 -0.12316E+00
  -C.5002E-01 -0.14848E+00 0.17331E-02 -0.13301E-02 -C.3385E+00 -0.16980E+00
THERE ARE 2 ACTIVE CONSTRAINTS
CONSTRAINT NUMBERS ARE
  10
  11
THERE ARE 0 VIOLATED CONSTRAINTS
THERE ARE 0 ACTIVE SIDE CONSTRAINTS
TERMINATION CRITERION
  ABS(CM11-1)/CM11 LESS THAN DELFUN FOR 30 ITERATIONS
  ABS(CM11-DELFUN) LESS THAN DELFUN FOR 30 ITERATIONS
NUMBER OF ITERATIONS = 73
OBJECTIVE FUNCTION WAS EVALUATED 491 TIMES
CONSTRAINT FUNCTIONS WERE EVALUATED 491 TIMES

```

```

OPTIMIZATION RESULTS
OBJECTIVE FUNCTION
GLOBAL LOCATION 1 FUNCTION VALUE 0.7005E+00
DESIGN VARIABLES
ID D. V. GLOBAL VAR. NO. LOWER BOUND VALUE +00 UPPER BOUND
1 1 1 1 0.2100E+01 0.2100E+01 0.2100E+01 0.2100E+01
2 2 2 2 0.2100E+01 0.2100E+01 0.2100E+01 0.2100E+01
3 3 3 3 0.2100E+01 0.2100E+01 0.2100E+01 0.2100E+01
DESIGN CONSTRAINTS
ID GLOBAL VAR. NO. LOWER BOUND UPPER BOUND
1 1 1 1 0.2100E+01 0.2100E+01 0.2100E+01 0.2100E+01
2 2 2 2 0.2100E+01 0.2100E+01 0.2100E+01 0.2100E+01
3 3 3 3 0.2100E+01 0.2100E+01 0.2100E+01 0.2100E+01

```


THE

PROGRAM CALLS TO ANALYZE
ICALL CALLS
1 452

APPENDIX F

ANALIZ CODES--DESIGN CASE NO. 2

```

SUBROUTINE ANALIZ(ICALC)
  INTEGER*4 ICALC
  REAL*4
  1  ETAD,WEIGHT,AEDVAD,DIA,N,PE,FOIVC,US,TC75R,V,
  2  RJCNU,RJCNU,R75RCL,R75RCU,AEAOCL,AEACCU,TC75CL,TC75CU,
  3  FCWBL,DIA,ACNU,AEACV,TCSTRS,RJ,
  4  VKTTC,WT,Z,WATRC,WATNU,TEMP,NGSCRW,HCL,PATM,
  5  PWATVA,PROMAT,DIALIM,ETARR,AEACMN,TC75MN,SC;
  COMMON /GLOECH/ETAD,WEIGHT,AEDVAD,DIA,N,PE,FOIVC,US,TC75R,V,RJCNU,
  1  RJCNU,R75RCL,R75RCU,AEAOCL,AEACCU,TC75CL,TC75CU,PWMBAL,DIA,ACNU,
  2  AEACCU,V,TCSTRS,RJ
  1  PROMAT,DIALIM,ETARR,AEACMN,TC75MN,SC
  THIS SUBROUTINE, COUPLED WITH CUPE/COMIN, CONSTATUTES ANALYSIS
  METHOD FOR "DESIGN CASE 2" PROPELLER SELECTION PROBLEMS
  INFL-INITIALIZATION PHASE
  PI1=3.14159264
  IF(.NOT.(ICALC.EQ.1))GO TO 1
  SET "DESIGN CASE 2" PARAMETERS
  ENVIRONMENTAL
  TEMP=64.4
  WATNU=1.9852
  WATNU=,000011500
  PATM=12.657
  PWATVA=.295435251
  PROPELLER PARAMETERS
  Z=6.0
  PRCMAT=5.0
  HULL PARAMETERS
  WT=C.22
  TC=C.11
  ETARR=1.025
  NGSCRW=1.0
  HCL=21.9827
  DIALIM=30.0
  SET DESIGN VARIABLES FELD FIXED FOR "DESIGN CASE 2"

```

APP0C490
 APP0C500
 APP0C510
 APP0C520
 APP0C530
 APP0C540
 APP0C550
 APP0C560
 APP0C570
 APP0C580
 APP0C590
 APP0C600
 APP0C610
 APP0C620
 APP0C630
 APP0C640
 APP0C650
 APP0C660
 APP0C670
 APP0C680
 APP0C690
 APP0C700
 APP0C710
 APP0C720
 APP0C730
 APP0C740
 APP0C750
 APP0C760
 APP0C770
 APP0C780
 APP0C790
 APP0C800
 APP0C810
 APP0C820
 APP0C830
 APP0C840
 APP0C850
 APP0C860
 APP0C870
 APP0C880
 APP0C890
 APP0C900
 APP0C910
 APP0C920
 APP0C930
 APP0C940
 APP0C950
 APP0C960

QS=121C129.835
 N=110.C
 VK=20.641C256
 V=1.68E*VK

 END OF INPUT-INITIALIZATION PHASE

 GO TO 3

 EXECUTION PHASE

 1 CONTINUE
 IF(.NOT.(ICALC.EC.2))GC TO 2
 TC75R=(10.C185-0.C0125*Z1)*Z1/(2.073*AEDVAG)
 CALL RICAL(DIA)
 CALL CF75RAIC75R,R75R
 CALL REY75RAIC75R,R75R
 CALL CCEFFSAIRJ,KY,KY
 CALL CFWEFFSAIRJ,KY,KY
 CALL CALCPKIRJ,KY
 CALL JCNA(RJ,RJCNL,RJCNJ)
 CALL REYCNAR75R,R75RCL,R75RCU
 CALL EXTCNAR75R,R75RCL,R75RCU
 CALL BLPOW2(KC,PCMBAL)
 CALL DICNUAID(IACNU)
 CALL CAVCNAR75R,R75RCL,R75RCU
 CALL STRCNAR75R,R75RCL,R75RCU

 END OF EXECUTION PHASE

 GO TO 3

 2 CONTINUE

 OUTPUT-RESULT PHASE

 VK=V/1.688
 VAK=(1.0-KT)*VK
 PC=(2.C*PI)*QS*N/33000.0
 WRITE(6,90001)
 WRITE(6,90002) TEMP,WATKQ,WATNU,PATM,PWATVA
 WRITE(6,90003) HT,TD,ETARR,NOSCRW,HCL,DIALIM
 WRITE(6,90004) Z
 IF(.NOT.(PRGMAT.EC.1.0))GO TO 81
 WRITE(6,90005) SC
 GC TO 86
 CCNTINLE
 IF(.NOT.(PRGMAT.EC.2.0))GC TO 82

CC
 CC
 CC
 C
 C

CC
 CC
 CC
 C
 C

81


```

SUBROUTINE ANALIZ(ICALC)
INTEGER*4 ICALC
REAL*4 ETAG,WEIGHT,AEDVAD,DIA,N,PE,POIVE,QS,TC75R,V,
1 RJC�L,RJCNU,R75FCL,V,TCSTRS,RJ,
2 FCWBL,DIACNU,AEACCV,V,TCSTRS,RJ,
3 VK,T,WT,Z,WATRG,WATNU,NGS,CRW,HCL,PATM,
4 PHATVA,PROMAT,DIALIM,ETARR,AEADGN,TC75MN,SC,
5 C75R,R75R,KI,KG,PD,VAK
COMMON /GLOFCM/ETAG,WEIGHT,AEDVAD,DIA,N,PE,FUIVU,WS,TC75K,V,RJC�L,
1 RJCNU,R75RCL,R75RCU,AEACCL,AEACCU,TC75CL,TC75CU,POMBAL,CIACNU,
2 AEACCV,TCSTRS,RJ
COMMON /PARAM/VK,TD,WI,Z,WATRO,WATNU,TEMP,NCSCRW,HCL,PATM,PHATVA,
1 PROMAT,DIALIM,ETARR,AEADGN,TC75MN,SC

THIS SUBROUTINE IS COUPLED WITH COPEX/COMMIN, CONSTITUTES ANALYSIS
METHOD FOR "DESIGN CASE 2" PROPELLER SELECTION PROBLEMS

INPLT-INITIALIZATION PHASE

PII=3.14159264
IF(.NOT.(ICALC.EQ.1))GO TO 1

SET "DESIGN CASE 2" PARAMETERS

ENVIRONMENTAL

TEMP=64.4
WATRG=1.9852
WATNU=.000011500
PATM=14.697
PHATVA=.295435251

PROPELLER PARAMETERS

Z=6.0
PRCMAT=5.0

HULL PARAMETERS

WT=C.21
TL=C.11
ETARR=1.025
NCSCRW=1.0
HCL=21.9827
DIALIM=30.0

SET DESIGN VARIABLES FELD FIXED FOR "DESIGN CASE 2"

```

APP02200
APP02210
APP02220
APP02230
APP02240
APP02250
APP02260
APP02270
APP02280
APP02290
APP02300
APP02310
APP02320
APP02330
APP02340
APP02350
APP02360
APP02370
APP02380
APP02390
APP02400
APP02410
APP02420
APP02430
APP02440
APP02450
APP02460
APP02470
APP02480
APP02490
APP02500
APP02510
APP02520
APP02530
APP02540
APP02550
APP02560
APP02570
APP02580
APP02590
APP02600
APP02610
APP02620
APP02630
APP02640
APP02650
APP02660
APP02670

```

CC      CS=121(129.835
CC      N=110.C
CC      VK=20.(6410256
CC      V=1.686*VK
CC
CC      ENE OF INPUT-INITIALIZATION PHASE
CC
CC      GO TO 3
CC
CC      EXECUTION PHASE
CC
1 CONTINUE
  IF(.NOT.(ICALC.EQ.2))GO TO 2
  TC75R=((10.0185-0.C0125*Z1)*Z1)/(2.073*AEQVAD)
  CALL RCAL(DIA)
  CALL RC75RA(C75R)
  CALL REY75RIC75R,R75R)
  CALL CCEFFSAIRJ,R75R,KI,KQ)
  CALL QMEFFAIRJ,KI,KQ,ETAD)
  CALL CALCPE(KI,PE)
  CALL JCNAL(RJ,RJCNL,RJCNUI)
  CALL REVCNAR75R,R75RCL,R75RCUI)
  CALL ETCNINZ.AEQVAD,TC75R,AEACCL,AEACCU,TC75CL,TC75CU)
  CALL BIPOM2(KC,POMBAL)
  CALL DIGNUA(DIACNU)
  CALL CAVCNNA(KI,AEACCV)
  CALL STRCNK(KC,KI,C75R,TCSTKS)
  ENE OF EXECUTION PHASE
CC
CC      GO TO 3
CC      2 CONTINUE
CC
CC      OUTPUT-RESULT PHASE
CC
  VK=V/1.686
  VAK=(1.0-WTI)*VK
  PC=(2.C*PII*QS*N)/33000.0
  WRITE(6,90001)
  WRITE(6,90002) TEMP,WTFR,WTNU,FATM,PHATVA
  WRITE(6,90003) MT,TD,ETARR,NOSCRW,HCL,DIALIM
  IF(.NOT.(PRGMAT.EQ.1.0))GO TO 81
  GC TC 86
  CC INLE
  IF(.NOT.(PRGMAT.EQ.2.0))GO TO 82
  81

```



```

82      WRITE(6,5006)SC
      GC TC E6
      CCNTINLE
      IF(.NOT.(PRMAT.EQ.3.C)IGC TO E3
      WRITE(6,5007)SC
      GC TC E6
      CCNTINLE
      IF(.NOT.(PRMAT.EQ.4.O)IGC TO E4
      WRITE(6,5008)SC
      GC TC E6
      CCNTINLE
      IF(.NOT.(PRMAT.EQ.5.C)IGC TO E5
      WRITE(6,5009)SC
      GC TC E6
      CCNTINLE
      WRITE(6,5010)
      CCNTINLE
      WRITE(6,9011)PE,V,VK,VAK,N,QS,PD,RJ,KT,KQ,ETAO,R75R,DIA,
      WRITE(6,9012)DIALIM,AEADNM,TC75R
      1
      3 CONTINUE
      RETURN

C
C
C MISCELLANEOUS FORMAT STATEMENTS
9000 FORMAT(1X,OPTIMIZATION RESULTS ----- DESIGN CASE NU:2.1,/,
1
9001 FORMAT(1X,DESIGN VARIABLES SPECIFIED: QS,N,V,TC75R:,,/,
1
9002 FORMAT(1X,ENVIRONMENTAL PARAMETERS: TEMP (DEG F):,22X,.,=,/,
1
2
3
4
5
9003 FORMAT(1X,1X,25X,DENSITY (LBF-SEC2/FT4):,12X,.,=,F10.4,/,
1
2
3
4
5
1X,25X,VISCOSITY (FT2/SEC):,15X,.,=,E16.9,/,F10.4,/,
1X,25X,ATMOSPHERIC PRESSURE (PSIA):,7X,.,=,F10.4,/,
1X,25X,WATER VAPORIZATION PRESSURE (PSIA):,7X,.,=,F10.4,/,
1X,25X,PARAMETERS: IONIZATION FRACTION:,,21X,.,=,F10.4,/,
1X,25X,THRUST REDUCTION FRACTION:,,9X,.,=,F10.4,/,
1X,25X,RELATIVE CF PROPELLERS EFFICIENCY:,,6X,.,=,F10.4,/,
1X,25X,NUMBER OF PROPELLERS:,,14X,.,=,F10.1,/,
1X,25X,DEPTH TO SHAFT CENTERLINE (FT):,,4X,.,=,F10.4,/,
1X,25X,DIAMETER LIMIT (FT):,,15X,.,=,F10.4,/,
9004 FORMAT(1X,PROPELLER PARAMETERS:,,8X,.,NUMBER OF BLADES,18X,.,=,
1
9005 FORMAT(1X,1X,25X,MATERIAL TYPE:,,21X,.,= CAST IRON:,,/,
1
9006 FORMAT(1X,25X,ALLOWABLE STRESS (PSI):,12X,.,=,F10.1,/,
1
9007 FORMAT(1X,25X,MATERIAL TYPE:,,21X,.,= CAST STEEL:,,/,
1
2
3
4
5
1X,25X,ALLOWABLE STRESS (PSI):,12X,.,=,F10.1,/,
1X,25X,MATERIAL TYPE:,,21X,.,= BRONZE:,,/,
1
2
3
4
5
1X,25X,ALLOWABLE STRESS (PSI):,12X,.,=,F10.1,/,

```

```

APP02680
APP02690
APP02700
APP02710
APP02720
APP02730
APP02740
APP02750
APP02760
APP02770
APP02780
APP02790
APP02800
APP02810
APP02820
APP02830
APP02840
APP02850
APP02860
APP02870
APP02880
APP02890
APP02900
APP02910
APP02920
APP02930
APP02940
APP02950
APP02960
APP02970
APP02980
APP02990
APP03000
APP03010
APP03020
APP03030
APP03040
APP03050
APP03060
APP03070
APP03080
APP03090
APP03100
APP03110
APP03120
APP03130
APP03140
APP03150

```



```

SUBROUTINE ANALIZICALC
  INTEGER*4 I,CALC
  REAL*4 ETAO,WEIGHT,AEDVAD,DIA,N,PE,FDIVL,GS,TC75R,V,
1  FJCNL,RJCNL,R75RCL,R75RCU,AEAOCL,AEALCU,TC75CL,TC75CU,
2  FJCNL,RJCNL,R75RCL,R75RCU,AEAOCL,AEALCU,TC75CL,TC75CU,
3  FJCNL,RJCNL,R75RCL,R75RCU,AEAOCL,AEALCU,TC75CL,TC75CU,
4  FJCNL,RJCNL,R75RCL,R75RCU,AEAOCL,AEALCU,TC75CL,TC75CU,
5  FJCNL,RJCNL,R75RCL,R75RCU,AEAOCL,AEALCU,TC75CL,TC75CU,
  COMMON /GLOECM/ETAO,WEIGHT,AEDVAD,DIA,N,PE,FDIVL,GS,TC75R,V,RJCNL,
1  RJCNU,R75RCL,R75RCU,AEAOCL,AEALCU,TC75CL,TC75CU,POMBAL,DIACNU,
2  AEACCV,TCSTFS,RJ
  COMMON /FARM/VK,TC,WI,Z,WAIRO,WATNU,TEMP,NCSRW,HCL,PATM,PWATVA,
1  PROMAT,DIALIM,ETARR,AEAGN,TC75MN,SC
  THIS SUBROUTINE, COUPLED WITH CPES/COMIN, CONSTITUTES ANALYSIS
  METHOD FOR "DESIGN CASE 2" PROPELLER SELECTION PROBLEMS
  INPUT-INITIALIZATION PHASE
  PI=3.14159264
  IF(.NOT.(ICALC.EQ.1))GO TO 1
  SET "DESIGN CASE 2" PARAMETERS
  ENVIRONMENTAL
  TEMP=64.4
  WAIRO=1.9852
  WATNU=.000011900
  PATM=14.657
  PWATVA=.255435291
  PROPELLER PARAMETERS
  Z=4.0
  PRCMAT=5.0
  HULL PARAMETERS
  WT=0.22
  TC=C.12
  ETARR=1.025
  NCSRW=1.0
  HCL=21.5827
  DIALIM=30.0
  SET DESIGN VARIABLES HELD FIXED FOR "DESIGN CASE 2"

```

APP0351J
 APP0352J
 APP0353J
 APP0354J
 APP0355J
 APP0356J
 APP0357J
 APP0358J
 APP0359J
 APP0400J
 APP0401J
 APP0402J
 APP0403J
 APP0404J
 APP0405J
 APP0406J
 APP0407J
 APP0408J
 APP0409J
 APP0410J
 APP0411J
 APP0412J
 APP0413J
 APP0414J
 APP0415J
 APP0416J
 APP0417J
 APP0418J
 APP0419J
 APP0420J
 APP0421J
 APP0422J
 APP0423J
 APP0424J
 APP0425J
 APP0426J
 APP0427J
 APP0428J
 APP0429J
 APP0430J
 APP0431J
 APP0432J
 APP0433J
 APP0434J
 APP0435J
 APP0436J
 APP0437J
 APP0438J

QS=J21C125.835
 N=110.C
 END OF INPUT-INITIALIZATION PHASE
 GO TO 3
 EXECUTION PHASE
 1 CONTINUE
 IF(.NOT.(ICALC.EQ.2))GC TO 2
 CALL RECAL(DIAL)
 CALL CF75RA(C75R)
 CALL REY75R(C75R,R75R)
 CALL CEESA(RJ,R75R,KT,KQ)
 CALL OFMEFF(RJ,KT,KQ,ETAD)
 CALL CALCP(KT,PE)
 CALL JCNA(RJ,R75R,RJCNL,RJCNJ)
 CALL REYCNAR(R75R,R75RCL,R75RCU)
 CALL EXTCCN(Z,AEDVAD,TC75R,AEACCL,AEACCU,TC75CL,TC75CU)
 CALL BLPOMZ(KC,POMBAL)
 CALL DICNUA(DIACNU)
 CALL CAVCNA(KT,AEADCV)
 CALL STRCNA(KC,C75R,TCSTRS)
 END OF EXECUTION PHASE
 GO TO 2
 2 CONTINUE
 OUTPUT-RESULT PHASE
 VK=V/1.688
 VAK=(1.0-WT)*VK
 PC=(2.0*PI*QS*N)/33000.0
 WRITE(C,9000)
 WRITE(C,9001)
 WRITE(C,9002)TEMP,WATRO,MAINU,PAIM,PMAIVA
 WRITE(C,9003)WT,TD,ETARR,NOSCRW,HCL,DIALIM
 IF(.NOT.(PROMAT.EQ.1.0))GC TO 81
 GC TO 86
 CCATINLE
 IF(.NOT.(PROMAT.EQ.2.0))GC TO 82
 GC TO 86
 CCATINLE
 81
 82


```

SUBROUTINE ANALIZ(ICALC)
  INTEGER*4 ICALC
  REAL*4
1  RJCNU, RJCNU, R75RCL, AEDVAD, CIA, N, PE, PD1VC, QS, TC75R, V,
2  FCMBAL, DIACNU, AEAOCV, TCSTRS, RJ
3  WKITIC, WT, Z, NATRC, WATNU, TEMP, NCSCRW, HCL, PAIM,
4  PNATVA, PRGMAT, DIALIM, ETARR, AEAOMN, TC75MN, SC,
5  C75R, R75R, KI, KC, PD, VAK
  COMMON /GLOECM/ ETAO, WEIGHT, AEDVAD, DIA, N, PE, PD1VO, QS, TC75R, V, KJCNL,
1  RJCNU, R75RCL, R75RCU, AEAOCV, TC75CL, TC75CU, PDWBAL, DIACNU,
2  AEAOCV, TCSTRS, RJ
  COMMON /PARAM/VK, TO, WT, Z, WATRO, NATNU, TEPP, NCSCRW, HCL, PAIM, PNATVA,
1  PRGMAT, DIALIM, ETARR, AEAOMN, TC75MN, SC

  THIS SUBROUTINE COUPLED WITH COPEX/COMPIN, CONSTITUTES ANALYSIS
  METHOD FOR "DESIGN CASE 2" PROPELLER SELECTION PROBLEMS

  INPUT-INITIALIZATION PHASE

  PI=3.14159264
  IF (.NOT. (ICALC.EQ.1)) GO TO 1

  SET "DESIGN CASE 2" PARAMETERS

  ENVIRONMENTAL
    TEMP=64.4
    WATRO=1.9852
    NATNU=.000011900
    PAIM=14.697
    PNATVA=.295435291

  PROPELLER PARAMETERS
    Z=C.0
    PRGMAT=5.0

  HULL PARAMETERS
    WT=C.22
    YC=C.15
    ETARR=1.025
    NCSCRW=1.0
    HCL=21.9827
    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

```

```

CC      QS=121(125.835
CC      N=110.0
CC      ENC OF INPUT-INITIALIZATION PHASE
C      GO TO 3
C      EXECUTION PHASE
C      1 CONTINUE
C      IF(.NOT.(ICALC.EC.2))GC TO 2
C      CALL RCAL(DIAL)
C      CALL CF75RA(C75R)
C      CALL REY75R(C75R,R75R)
C      CALL CEF75R(R75R,KT,KQ)
C      CALL OFWFF(R75R,KT,KQ,ETAO)
C      CALL CALCP(E75R,KT,KQ)
C      CALL JCN(R75R,RJCN)
C      CALL REVCNA(R75R,R75RCL,R75RCU)
C      CALL EXTCCN(Z,AEADVAO,TC75R,AEACCL,AEADCU,TC75CL,TC75CU)
C      CALL BLPOW2(KC,PONBAL)
C      CALL DICNUA(DIACNU)
C      CALL CAVCNA(KT,AEADCV)
C      CALL STRCNK(KC,KT,C75R,TCSTRS)
C      ENC OF EXECUTION PHASE
CC      GO TO 3
CC      2 CONTINUE
CC      OUTPUT-RESULT PHASE
CC      VK=V/1.688
CC      VAK=(1.0-WT)*VK
CC      PC=(2.0-PI)*QS*N/33000.0
CC      WRITE(6,90001)
CC      WRITE(6,90002) TEMP,WAIRG,WAIRU,PATM,PWATVA
CC      WRITE(6,90003) WT,TD,ETARR,NGSCRW,HCL,DIALIM
CC      IF(.NOT.(PRGMAT.EC.1.0))GC TO 81
CC      GC TO 86
CC      CCNTINLE
CC      IF(.NOT.(PRGMAT.EC.2.0))GC TO 82
CC      GC TO 86
CC      CCNTINLE
C      81
C      82

```

```

APP05590
APP05600
APP05610
APP05620
APP05630
APP05640
APP05650
APP05660
APP05670
APP05680
APP05690
APP05700
APP05710
APP05720
APP05730
APP05740
APP05750
APP05760
APP05770
APP05780
APP05790
APP05800
APP05810
APP05820
APP05830
APP05840
APP05850
APP05860
APP05870
APP05880
APP05890
APP05900
APP05910
APP05920
APP05930
APP05940
APP05950
APP05960
APP05970
APP05980
APP05990
APP06000
APP06010
APP06020
APP06030
APP06040
APP06050
APP06060

```


AD-A132 414 PRELIMINARY PROPELLER SELECTION USING THE WAGENINGEN
B-SCREW SERIES AND A GENERAL PURPOSE NON-LINEAR
OPTIMIZER(U) NAVAL POSTGRADUATE SCHOOL MONTEREY CA
UNCLASSIFIED M P SMITH JUN 83 F/G 13/10

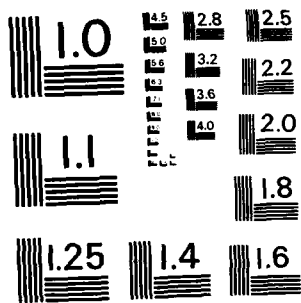
PRELIMINARY PROPELLER SELECTION USING THE WAGENINGEN
B-SCREW SERIES AND A GENERAL PURPOSE NON-LINEAR
OPTIMIZER(U) NAVAL POSTGRADUATE SCHOOL MONTEREY CA
M P SMITH JUN 83 F/G 13/1

UNCLASSIFIED

F/G 13/10

NL

END
DATE
FILMED
9 84
FBI



MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

CONTROL CARD IMAGES--DESIGN CASE NO. 2

288

-1.0	21	0.0	1.0
-1.0	+16	0.0	1.0
\$V	22	0.0	1.0
END	+16		

CENTRAL PROGRAM

F G R

ENGINEERING SYNTHESES

3718

WAGENJAGER B-SERIES PROPELLER OPTIMIZATICA

IMAGE

CARD

[illegible]

INPUT EXECUTION AVAILABLE
8 10000 10000
INPUT EXECUTION AVAILABLE
43 10000 10000

DESIGN VARIABLES SPECIFIED:
ENVIRONMENTAL PARAMETERS:

US.A.V. 1C75A

[illegible]

FULL PARAMETERS:

FACILITY

PROPELLER PARAMETERS:

NUMBER OF BLADES
AVAILABLE
TYPE
STRESS (PSI)

SELECTION VALUES:

[illegible]

CONSTRAINT VALUES:

MAX	MIN	FT	
514	40		5.000
46	10		5.999
17	0		5.000
75	0		0.06250

```

.....
C C P M I N
.....
FURTHER PROGRAM FOR
.....
CONSTRAINED FUNCTION MINIMIZATION
.....

```

```

INITIAL FUNCTION INFORMATION
OBJ = -C.118204E+00
DEJSTIC VARIATION 1A-VECTO 0.10000E+00 0.10000E+01
CONSTRAINT VALUES 1A-VECTO 1
1 -C.33500E-01 -0.97731E-00 -0.20000E+03 -0.17775E+03 C.10000E+00 -0.40000E+00
1 -C.33500E-01 -0.97731E-00 -0.20000E+03 -0.17775E+03

```

```

FINAL OPTIMIZATION INFORMATION
CBLJ = -C.65992E+00
DECISION VARIABLES (X-VECTOR)
C.0217E+00 0.8452E+00 0.5036E+00
CONSTRAINT VALUES (G-VECTOR)
-0.1610E+00 -0.3933E+00 -0.3493E+02 -0.3749E+03 -0.3671E+00 0.1777E-02
CONSTRAINT NUMBERS ARE
THERE ARE 0 VIOLATED CONSTRAINTS
THERE ARE 0 ACTIVE SIDE CONSTRAINTS
TERMINATION CRITERION
ADDITIONAL ITERATION LESS THAN DABFUN FOR 30 ITERATIONS
NUMBER OF ITERATIONS = 45
OBJECTIVE FUNCTION WAS EVALUATED 230 TIMES
CONSTRAINT FUNCTIONS WERE EVALUATED 230 TIMES

```


DESIGN VARIABLES SPECIFIED:
ENVIRONMENTAL PARAMETERS:

[illegible][illegible]

PROPELLER PARAMETERS:	NUMBER OF BLADES	4	STEEL
	MATERIAL	STAINLESS	
	ALLOWABLE STRESS (PSI)	1400.0	

SECRET
NOFORN
UNCLASSIFIED

100-443887-100

**MAX
HIN**

PROGRAM CALLS TO ANALYZE
ICALL CALLS
2
3

NAME	DATE	TIME	LOCATION	IMAGE
...	...	...	...	...

302

INPUT	EXECUTION	AVAILABLE	INPUT	EXECUTION	AVAILABLE
87	450	10000	83	100	1000

305

```

.....
C C P M I N
.....
FUNKIN PROGRAM FOR
.....
CONSTRAINED FUNCTION MINIMIZATION
.....

```

INITIAL FUNCTION INFORMATION

COJ = -C.11202E+02

DECSICA VARIABLES AT VECTOR

C.4200E+00 0.10000E+01

CONSTRAINT VALUES (C-VECTOR)

|| -0.9250E-01 -0.4775E+00 -0.2020E+02 -0.2787E+03 0.1000E+00 -0.4000E+00

```

FINAL OPTIMIZATION INFORMATION
OBJ = -C.665992E+00
DESIGN VARIABLES IN VECTOR
C.8C177E+00 0.64752E+00 0.40364E+00
CONSTRAINT VALUES IN VECTOR
C.1810E+00 -0.8162E-01 -0.24820E+02 -0.9719E+03 -0.30170E+00 0.17773E-02
THERE ARE 3 ACTIVE CONSTRAINTS
CONSTRAINT NUMBERS ARE
THERE ARE 0 VIOLATED CONSTRAINTS
THERE ARE 0 ACTIVE SIDE CONSTRAINTS
TERMINATION CRITERION
ABSCJ(1)-0.017-1.1) LESS THAN DAMFUN FOR 30 ITERATIONS
NUMBER OF ITERATIONS = 45
OBJECTIVE FUNCTION WAS EVALUATED 230 TIMES
CONSTRAINT FUNCTIONS WERE EVALUATED 230 TIMES

```



```
OBJECTIVE FUNCTION 1
GLOBAL LOCATION      FUNCTION VALUE 0.66599E+00
```

```
OBJECTIVE FUNCTION 1
GLOBAL LOCATION      FUNCTION VALUE 0.66599E+00
```

DI
D. V. GLUBAL
VDR. NC.

DI
D. V. GLUBAL
VDR. NC.

[illegible]

10	GLOBAL VAR. NO.
1	1
2	2
3	3
4	4
5	5
6	6
7	7
8	8
9	9
10	10
11	11
12	12
13	13
14	14
15	15
16	16
17	17
18	18
19	19
20	20
21	21
22	22
23	23
24	24
25	25
26	26
27	27
28	28
29	29
30	30
31	31
32	32
33	33
34	34
35	35
36	36
37	37
38	38
39	39
40	40
41	41
42	42
43	43
44	44
45	45
46	46
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51	51
52	52
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56	56
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67	67
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78	78
79	79
80	80
81	81
82	82
83	83
84	84
85	85
86	86
87	87
88	88
89	89
90	90
91	91
92	92
93	93
94	94
95	95
96	96
97	97
98	98
99	99
100	100

10	GLOBAL VAR. NO.
1	1
2	2
3	3
4	4
5	5
6	6
7	7
8	8
9	9
10	10
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83	83
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85	85
86	86
87	87
88	88
89	89
90	90
91	91
92	92
93	93
94	94
95	95
96	96
97	97
98	98
99	99
100	100

[illegible]

PROGRAM CALLS TO ANALYZE
SCALE CALLS

CANL	IMAGE

IPNPL
LINDEJ
CILMIN

IPUBS
NACMA
THEA

TITLE: WAGENINGEN B-SERIES PAPERELLER OPTIMIZATION

COMPILED BY: J. H. VAN DER LINDEN
 DATE: 1970-10-10
 MACHINE: IBM 360-58
 DEPENDENT VARIABLE: PAPERELLE
 INDEPENDENT VARIABLE: PAPERELLE
 INITIAL VALUE: 10000000

CALCULATE: CUMULATIVE, NCALC
 VALUE: 10000000
 ANALYSIS: 1
 FUNCTION: 1
 FUNCTION SPACE: 1
 OPTIMIZATION: 1

OPTIMIZATION INFORMATION

GLOBAL VARIABLE NUMBER OF OBJECTIVE
 MULT. BY NEGATIVE INDICATIONS = 0.1000E+01
 CONFIN PARAMETERS (IF ZERO, COMMON DEFAULT WILL OVER-RIDE)
 IPRIOT 1000 IENCLR MICAL 30 LINCBS MACMAI MCGG
 FOUR 0.1000E+03 EOCUM 0.1000E+03 SI 0.1000E+02 LINIM 0.0
 STG 0.0 CUMIN 0.0 THETA 0.0 PH 0.0
 DESUN 0.0 DREFUN 0.0 ALPHAX 0.0 ABURJI 0.0
 DESIGN VARIABLE INFORMATION (PER-RIDE NUMBER INPUT)
 NON-ZERO INITIAL VALUE WILL BE USED
 NO. 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20
 VALUE 1.0000E+01 1.0000E+01 1.0000E+01 1.0000E+01 1.0000E+01 1.0000E+01 1.0000E+01 1.0000E+01 1.0000E+01 1.0000E+01 1.0000E+01 1.0000E+01 1.0000E+01 1.0000E+01 1.0000E+01 1.0000E+01 1.0000E+01 1.0000E+01 1.0000E+01
 LOWER 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00
 UPPER 1.0000E+01 1.0000E+01 1.0000E+01 1.0000E+01 1.0000E+01 1.0000E+01 1.0000E+01 1.0000E+01 1.0000E+01 1.0000E+01 1.0000E+01 1.0000E+01 1.0000E+01 1.0000E+01 1.0000E+01 1.0000E+01 1.0000E+01 1.0000E+01 1.0000E+01

DESIGN VARIABLES
 NO. 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20
 VALUE 1.0000E+01 1.0000E+01 1.0000E+01 1.0000E+01 1.0000E+01 1.0000E+01 1.0000E+01 1.0000E+01 1.0000E+01 1.0000E+01 1.0000E+01 1.0000E+01 1.0000E+01 1.0000E+01 1.0000E+01 1.0000E+01 1.0000E+01 1.0000E+01 1.0000E+01
 LOWER 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00
 UPPER 1.0000E+01 1.0000E+01 1.0000E+01 1.0000E+01 1.0000E+01 1.0000E+01 1.0000E+01 1.0000E+01 1.0000E+01 1.0000E+01 1.0000E+01 1.0000E+01 1.0000E+01 1.0000E+01 1.0000E+01 1.0000E+01 1.0000E+01 1.0000E+01 1.0000E+01

CONSTRAINT INFORMATION

THERE ARE 10 CONSTRAINTS
 NO. 1 2 3 4 5 6 7 8 9 10
 VALUE 1.0000E+01 1.0000E+01 1.0000E+01 1.0000E+01 1.0000E+01 1.0000E+01 1.0000E+01 1.0000E+01 1.0000E+01 1.0000E+01
 LOWER 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00
 UPPER 1.0000E+01 1.0000E+01 1.0000E+01 1.0000E+01 1.0000E+01 1.0000E+01 1.0000E+01 1.0000E+01 1.0000E+01 1.0000E+01

TOTAL REPEL OF CONSIDERING PARAMETERS - 14

• • ESTIPATIO DATA STORAGE REQUIREMENTS

INPUT EXECUTION BY	AVAILABLE	INPUT EXECUTION	INFLUENCE AVAILABLE
10000	57	10000	1000

315

2
3
4
5
6

FURTHER PROGRAM FOR

CONSTRAINED FUNCTION MINIMIZATION

INITIAL FLUXION INFORMATICA

[illegible]

```

FINAL OPTIMIZATION INFORMATION
OBJ = -C.77645E+01
LEGISLA VARIABLES (X-VECTOR)
|| C.75462E+00 0.99270E+00 0.11906E+01 0.52182E+02 C.49512E-01
CONSTRAINT VALUES (C-VECTOR)
|| -C.6284E+00 -0.3795E+00 -0.3795E-01 -0.3801E-03 -0.2755E+03 -0.2995E+03 -0.2777E+03
THERE ARE 2 ACTIVE CONSTRAINTS
CONSTRAINT NUMBERS ARE
THERE ARE 0 VIOLATED CONSTRAINTS
THERE ARE 0 ACTIVE SLICE CONSTRAINTS
TERMINATION CRITERION
|| -C.77645E+01 LESS THAN DELTA FOR 30 ITERATIONS
|| -C.77645E+01 LESS THAN DELTA FOR 30 ITERATIONS
NUMBER OF ITERATIONS = 80
OBJECTIVE FUNCTION WAS EVALUATED 544 TIMES
CONSTRAINT FUNCTIONS WERE EVALUATED 544 TIMES

```

OBJECTIVE FUNCTION : FUNCTION VALUE 0.75764E+00

OBJECTIVE FUNCTION :
GLOBAL LOCATION :

DESIGN VARIABLES

[illegible]

DESIGN CONSTRAINTS

DATA BUS

16-BIT ADDRESS BUS

UPPER 8-BIT ADDRESS

LOWER 8-BIT ADDRESS

GLOBAL NUM.

16-BIT ADDRESS DECODE

PROGRAM CALLS TO ANALYZE
CALL CALLS
142

324

```

.....
C L A M I N
.....
FURTHAN PROGRAM FOR
.....
CONSTRAINED FUNCTION MINIMIZATION
.....

```

INITIAL FUNCTION INFORMATION

OBJ = -0.218442E+00

DECISIA VARIABLES (X-VECTOR)

11 C-4000E+00 0.1000E+00 0.1000E+01 0.5000E+02 0.5000E+03

CONSTRAINT VALUES (G-VECTOR)

11 -0.3101E+00 -0.7755E+00 -0.1709E+00 0.7412E+03 10.1366E+03 5.1000E+00 0.2301E+01

```

FINAL OPTIMIZATION INFORMATION
CBAJ = -C.73297E+0C
DE{SILV.98121E+00 0.81138E+00 0.1030E+01 0.4965E+02 0.6343E-01
C.73297E+00 0.81138E+00 0.1030E+01 0.4965E+02 0.6343E-01
CONSTRAINT VALUES -VECTION-OF -0.7731E+03 -0.7731E+03 -0.7731E+03 -0.7731E+03
} -0.7731E+03 -0.7731E+03 -0.7731E+03 -0.7731E+03 -0.7731E+03 -0.7731E+03
THERE ARE 2 ACTIVE CONSTRAINTS
CONSTRAINT NUMBERS ARE
THERE ARE 0 VIOLATED CONSTRAINTS
THERE ARE 0 ACTIVE SIDE CONSTRAINTS
TERMINAL CRITERION -111 LESS THAN DABUM FOR 30 ITERATIONS
NUMBER OF ITERATIONS = 35
OBJECTIVE FUNCTION WAS EVALUATED 209 TIMES
CONSTRAINT FUNCTIONS WERE EVALUATED 209 TIMES

```

327

```

OPTIMIZATION RESULTS -----
DESIGN CASE NO. 2
SUBROUTINE "STRCK"

DESIGN VARIABLES SPECIFIED:
ENVIRONMENTAL PARAMETERS:
  US-A
  DENS (G/CC) = 6.430E-04
  VISC (G/CM SEC) = 0.1889997E-04
  VAPOR PRESSURE (PSIA) = 1.9970
  MAX PER VAPORIZATION PRESSURE (PSIA) = 0.2994

NULL PARAMETERS:
  WAKE FRICTION COEFFICIENT = 1.2000
  THERMAL EFFICIENCY = 1.0000
  NUMBER OF PROPELLERS = 1
  DEPTH OF SHIP CENTERLINE (FT) = 31.9827
  DIAPYCN LIFT (FT) = 31.0000

PROPELLER PARAMETERS:
  NUMBER OF BLADES = 2
  MATERIAL TYPE = STEEL
  ALLOWABLE STRESS (PSI) = 240000

SELECTION VALUES:
  PE (FT/SEC) = 240000
  V (FT/SEC) = 240000
  VA (FT/SEC) = 240000
  PD (FT/SEC) = 240000
  J = 1.0000
  K = 1.0000
  AL = 1.0000
  CRU (FT) = 240000
  CRU (FT) = 240000
  AL = 1.0000
  J = 1.0000

CONSTRAINT VALUES:
  MAX Q12 (FT) = 31.0000
  MIN Q12 (FT) = 31.0000
  MAX Q12 (FT) = 31.0000
  MIN Q12 (FT) = 31.0000
  
```

PROGRAM CALLS TO ANALYZE
ICALL CALLS
210
2

APPENDIX I

ANALIZ CODES--DESIGN CASE NO. 3

```

SUBROUTINE ANALIZ (ICALC)
  INTEGER*4 I, ICALC
  REAL*4 ETAO, WEIGHT, AEDVAD, DIA, N, PE, FDI, VC, QS, TC75R, V,
    RJCNU, RJCNU, R75RCL, R75RCL, AEAQCL, AEAQCL, TC75CL, TC75CU,
    FCWBL, DIACNU, AEAQCV, TCSTKS, RJ,
    VKITL, WITL, WATRC, WATNU, TEMP, NCS, CRW, HCL, PAIM,
    PWATVA, PROMAT, DIALIM, ETARK, AEAQMN, TC75MN, SCREQ,
    C75R, R75R, KT, KC, PD, TUEV, PLEEV, PLEEV, QS, TC75R, V, RJCNU,
    COMMON /GLOECM/ ETAC, WEIGHT, AEDVAD, DIA, N, PE, FDI, VC, QS, TC75R, V, RJCNU,
    1 RJCNU, R75RCL, R75RCL, AEAQCL, AEAQCL, TC75CL, TC75CU, POWBAL, DIACNU,
    2 AEAQCV, TCSTKS, RJ
    COMMON /PARAM/ VK, TD, WI, Z, WATRO, WATNU, TEMP, NCS, CRW, HCL, PAIM, PWATVA,
    1 PRCMAT, DIALIM, ETARR, AEAQMN, TC75MN, SC
  THIS SUBROUTINE, COUPLED WITH COPEX/COMIN, CONSTITUTES ANALYSIS
  METHOD FOR "DESIGN CASE 3" PROPELLER SELECTION PROBLEMS
  INFLT-INITIALIZATION PHASE
  PI1=3.14159264
  IF (.NOT. (ICALC.EQ.1)) GO TO 1
  SET "DESIGN CASE 3" PARAMETERS
  ENVIRONMENTAL
    TEMP=55.0
    WATRC=1.9905
    WATNU=2.000012817
    PAIM=14.7
    PWATVA=.247
  PROPELLER PARAMETERS
    Z=6.0
    PRCMAT=5.0
  FULL PARAMETERS
    WT=6.25
    TC=0.1725
    ETARR=1.025
    NCS, CRW=1.0
    HCL=19.0
  SET DESIGN VARIABLES HELD FIXED FOR "DESIGN CASE 3"
  PE=21252.6

```


APP0C570
 APP0C580
 APP0C590
 APP01000
 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

```

      WRITE(6,9005)ISC
      GC IC E6
      CCATINLE
      IF(.NOT.(PRMAT.EQ.2.0))GC TO E2
      WRITE(6,9006)ISC
      GC IC E6
      CCATINLE
      IF(.NOT.(PRMAT.EQ.3.0))GC TO E3
      WRITE(6,9007)ISC
      GC IC E6
      CCATINLE
      IF(.NOT.(PRMAT.EQ.4.0))GC TO E4
      WRITE(6,9008)ISC
      GC IC E6
      CCATINLE
      IF(.NOT.(PRMAT.EQ.5.0))GC TO E5
      WRITE(6,9009)ISC
      GC IC E6
      CCATINLE
      WRITE(6,9010)
      CCATINLE
      WRITE(6,9011)PE,V,N,QS,PD,ETACSP,RJ,KI,KQ,ETA0,K75K,DIA,
      POIVC,AEADVAO,TC75R,WEIGHT
      WRITE(6,9012)DIALIM,AEADOMN,TC75MN
      WRITE(6,9013)PEDEV,VK,QREC,N,PCREC
      3 CONTINUE
      RETURN
C
C MISCELLANEOUS FORMAT STATEMENTS
C
9000 FORMAT(1X,'OPTIMIZATION RESULTS -----'
1X,'DESIGN CASE NO. 3.2/'
1X,'SUBROUTINE "STRCNK",//)
9001 FORMAT(1X,'DESIGN VARIABLES SPECIFIED: PE,V,QS,N,DIA,//)
9002 FORMAT(1X,'ENVIRONMENTAL PARAMETERS:
1X,'TEMP (DEG F),22X,/=',
1X,'25X, DENSITY (LBF-SEC2/FT4),12X,/=',F10.4,/,
1X,'25X, VISCOSITY (FT2/SEC),15X,/=',E16.9,/,
1X,'25X, ATMOSPHERIC PRESSURE (PSIA),7X,/=',F10.4,/,
1X,'25X, WATER VAPORIZATION PRESSURE (PSIA),7X,/=',F10.4,/,
1X,'25X, WAKE FRACTION,21X,/=',F10.4,/,
1X,'25X, PARAMETERS:13X, WAKE FRACTION,9X,/=',F10.4,/,
1X,'25X, FULL THRU DEDUCTION FRACTION,9X,/=',F10.4,/,
1X,'25X, RELATIVE ROTATIVE EFFICIENCY,6X,/=',F10.4,/,
1X,'25X, NUMBER OF PROPELLERS,14X,/=',F10.4,/,
1X,'25X, LEPTHC SHAFI CENTERLINE (FT),14X,/=',F10.4,/,
1X,'25X, LEPTHC SHAFI LIMIT (FT),15X,/=',F10.4,/,
1X,'25X, DIAMETER OF BLADES,18X,/=',
9004 1 FORMAT(1X,'FROPELLER PARAMETERS:8X, NUMBER OF BLADES,18X,/=',
1X,'25X, MATERIAL TYPE,21X,/= CAST IRON,/,
9005 1 FORMAT(1X,'25X, MATERIAL TYPE,21X,/= CAST IRON,/,
  
```


APPENDIX J

CONTROL CARD IMAGES--DESIGN CASE NO. 3

SA	TITLE	GEN	B-SERIES	PKOPPELLER	CPTIMIZATION	IPDBG
\$B	WAGNING	NCALC	NDV	NSV	N2VAR	IPDBG
\$C	IPRINT	1	ITPAX	ICNDIR	NSCAL	NACMX1
\$D1	FDCH	1	ICOO	CT	CTMIN	15
\$D2	DELFUN	1	FDCHM	CT	CTMIN	THETA
\$E	NDVTOT	3	COI	ALPHAX	ABCBJI	
\$F	VLB	3	CABFUN	SGNQPT		
\$G	ADSSGN	12	ICBJ	-1.0	SCAL	
		3	1UB	1.0	1.0	
		7	1.1	1.0	1.0	
		9	1.4	1.3	1.0	
			1.5	0.01CC	0.100	
\$H	NCONS	12	IDSGN	AMULT		
\$I1	ICCN	12	3	1.0		
\$I2	BL	11	9	1.0		
-1.0	+11	11	JCON	LCCN	SCAL2	
-1.0	+12	12	SCAL1	BU	1.0	
-1.0	+13	13	1.0	0.0	1.0	
-1.0	+14	14	1.0	0.0	1.0	
-1.0	+15	15	1.0	0.0	1.0	
-1.0	+16	16	1.0	0.0	1.0	
-1.0	+17	17	1.0	0.0	1.0	
-1.0	+18	18	1.0	0.0	1.0	
-1.0	+19	19	1.0	0.0	1.0	
-1.0	+20	20	1.0	0.0	1.0	
-1.0	+21	21	1.0	0.0	1.0	
-1.0	+22	22	1.0	0.0	1.0	
-1.0	+23	23	1.0	0.0	1.0	
-1.0	+24	24	1.0	0.0	1.0	
-1.0	+25	25	1.0	0.0	1.0	
-1.0	+26	26	1.0	0.0	1.0	
-1.0	+27	27	1.0	0.0	1.0	
-1.0	+28	28	1.0	0.0	1.0	
-1.0	+29	29	1.0	0.0	1.0	
-1.0	+30	30	1.0	0.0	1.0	
-1.0	+31	31	1.0	0.0	1.0	
-1.0	+32	32	1.0	0.0	1.0	
-1.0	+33	33	1.0	0.0	1.0	
-1.0	+34	34	1.0	0.0	1.0	
-1.0	+35	35	1.0	0.0	1.0	
-1.0	+36	36	1.0	0.0	1.0	
-1.0	+37	37	1.0	0.0	1.0	
-1.0	+38	38	1.0	0.0	1.0	
-1.0	+39	39	1.0	0.0	1.0	
-1.0	+40	40	1.0	0.0	1.0	
-1.0	+41	41	1.0	0.0	1.0	
-1.0	+42	42	1.0	0.0	1.0	
-1.0	+43	43	1.0	0.0	1.0	
-1.0	+44	44	1.0	0.0	1.0	
-1.0	+45	45	1.0	0.0	1.0	
-1.0	+46	46	1.0	0.0	1.0	
-1.0	+47	47	1.0	0.0	1.0	
-1.0	+48	48	1.0	0.0	1.0	
-1.0	+49	49	1.0	0.0	1.0	
-1.0	+50	50	1.0	0.0	1.0	
-1.0	+51	51	1.0	0.0	1.0	
-1.0	+52	52	1.0	0.0	1.0	
-1.0	+53	53	1.0	0.0	1.0	
-1.0	+54	54	1.0	0.0	1.0	
-1.0	+55	55	1.0	0.0	1.0	
-1.0	+56	56	1.0	0.0	1.0	
-1.0	+57	57	1.0	0.0	1.0	
-1.0	+58	58	1.0	0.0	1.0	
-1.0	+59	59	1.0	0.0	1.0	
-1.0	+60	60	1.0	0.0	1.0	
-1.0	+61	61	1.0	0.0	1.0	
-1.0	+62	62	1.0	0.0	1.0	
-1.0	+63	63	1.0	0.0	1.0	
-1.0	+64	64	1.0	0.0	1.0	
-1.0	+65	65	1.0	0.0	1.0	
-1.0	+66	66	1.0	0.0	1.0	
-1.0	+67	67	1.0	0.0	1.0	
-1.0	+68	68	1.0	0.0	1.0	
-1.0	+69	69	1.0	0.0	1.0	
-1.0	+70	70	1.0	0.0	1.0	
-1.0	+71	71	1.0	0.0	1.0	
-1.0	+72	72	1.0	0.0	1.0	
-1.0	+73	73	1.0	0.0	1.0	
-1.0	+74	74	1.0	0.0	1.0	
-1.0	+75	75	1.0	0.0	1.0	
-1.0	+76	76	1.0	0.0	1.0	
-1.0	+77	77	1.0	0.0	1.0	
-1.0	+78	78	1.0	0.0	1.0	
-1.0	+79	79	1.0	0.0	1.0	
-1.0	+80	80	1.0	0.0	1.0	
-1.0	+81	81	1.0	0.0	1.0	
-1.0	+82	82	1.0	0.0	1.0	
-1.0	+83	83	1.0	0.0	1.0	
-1.0	+84	84	1.0	0.0	1.0	
-1.0	+85	85	1.0	0.0	1.0	
-1.0	+86	86	1.0	0.0	1.0	
-1.0	+87	87	1.0	0.0	1.0	
-1.0	+88	88	1.0	0.0	1.0	
-1.0	+89	89	1.0	0.0	1.0	
-1.0	+90	90	1.0	0.0	1.0	
-1.0	+91	91	1.0	0.0	1.0	
-1.0	+92	92	1.0	0.0	1.0	
-1.0	+93	93	1.0	0.0	1.0	
-1.0	+94	94	1.0	0.0	1.0	
-1.0	+95	95	1.0	0.0	1.0	
-1.0	+96	96	1.0	0.0	1.0	
-1.0	+97	97	1.0	0.0	1.0	
-1.0	+98	98	1.0	0.0	1.0	
-1.0	+99	99	1.0	0.0	1.0	
-1.0	+100	100	1.0	0.0	1.0	

\$V
END

COPEs OUTPUT--DESIGN CASE NO. 3

```

SSSSS      FFFFFF      OOOO    WWWWWW
SSSSS      FFFFFF      OOOO    WWWWWW
SSSSS      FF       FF   OO     WWWWWW
SSSSS      FF       FF   OO     WWWWWW
SSSSS      FF       FF   OO     WWWWWW

```

CONTROL PROGRAM
FURN
ENGINEERING SYNTHESES

WAGENINGA B-SERIES PROPELLER OPTIMIZATION

11466

11466

12	FILE	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86	87	88	89	90	91	92	93	94	95	96	97	98	99	100
1	NAME	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86	87	88	89	90	91	92	93	94	95	96	97	98	99	100
1	NAME	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86	87	88	89	90	91	92	93	94	95	96	97	98	99	100
1	NAME	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86	87	88	89	90	91	92	93	94	95	96	97	98	99	100
1	NAME	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86	87	88	89	90	91	92	93	94	95	96	97	98	99	100
1	NAME	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75</																									

OPTIMIZATION RESULTS ----- DESIGN CASE NO. 2
SUBROUTINE "STCRN"

DESIGN VARIABLE SPECIFIED: PELLCS MEDIA

ENVIRONMENTAL PARAMETERS:

TEMP (DEG F) 55.0000
WIND VELOCITY (FT/SEC) 0.1217034E+04
WIND DIRECTION (DEG) 15.0000
WATER VAPORIZATION PRESSURE (PSIA) 0.2490

PULL PARAMETERS:

WAKE FRACTION ON FRACTION 0.2200
HULL VENTILATION EFFICIENCY 1.0000
NUMBER OF PADDLES 1.0
DEPTH OF CHUTE (FT) 15.0000
DIAPETER (IN) 0.0

PROPELLER PARAMETERS:

NUMBER OF BLADES 6
ALLOWABLE STRESS (PSI) 210000 STEEL

SELECTION VALUES:

PE (HPI) SEC 2.2970
W (HPI) SEC 10.3000
US (FT) (HPI) 100000.0
PD (HPI) 30000.05
ETAL SPECIFIED C.6527
J 0.8200
K 0.2000
ETA (HPI) C.6583
P/D (HPI) 0.8500
AE (HPI) 1.0000
BLADE HEIGHT (LBF) 2563.1

CONSTRAINT VALUES:

MAX C/A (FT) 1.0
MIN P/D (HPI) 0.23838

PROPELLER "CENTIS":

PE DEVELOPED (HPI) 24256.0
US REQUIRED (FT-LBF) 117034.0
PD REQUIRED (HPI) 37103.42

[illegible]

```

FINAL OPTIMIZATION INFORMATION
END = C.12020E+05
DECISION VARIABLES (X-VALUE)
11 C.7444E+00 0.1101E+01 0.7938E-01
CONSTRAINT VALUES (C-VALUE)
11 -C.5801E+00 -0.5018E+00 -0.1345E+02 -0.7022E+02 -0.2944E+03 -0.2501E+04
71 -C.5549E-01 -0.1753E+00 0.5047E-02 -0.0165E-01 0.1621E-01 -0.1291E+00
THERE ARE 1 ACTIVE CONSTRAINTS
CONSTRAINT NUMBERS ARE
6
THERE ARE 2 VIOLATED CONSTRAINTS
CONSTRAINT NUMBERS ARE
9 11
THERE ARE 0 ACTIVE SIDE CONSTRAINTS
TERMINATION CRITERION
TEN CONSECUTIVE ITERATIONS FAILED TO PROVIDE A FEASIBLE DESIGN
NUMBER OF ITERATIONS = 10
OBJECTIVE FUNCTION WAS EVALUATED 37 TIMES
CONSTRAINT FUNCTIONS WERE EVALUATED 37 TIMES

```

OPTIMIZATION RESULTS

OBJECTIVE FUNCTION 2 FUNCTION VALUE 0.12843E+05
GLOBAL LOCATION

DESIGN VARIABLES

ID	D.V. NO.	GLOBAL VAR. NO.	LOWER BOUND	VALUE	UPPER BOUND
1	1	1	0.2000E+00	0.744E+00	0.1000E+01
2	2	2	0.1000E+00	0.813E+01	0.1000E+01
3	3	3	0.1000E+00	0.133E+01	0.1000E+00

DESIGN CONSTRAINTS

ID	GLOBAL VAR. NO.	LOWER BOUND	UPPER BOUND
1	1	0.0000E+00	0.0000E+00
2	2	0.0000E+00	0.0000E+00
3	3	0.0000E+00	0.0000E+00
4	4	0.0000E+00	0.0000E+00
5	5	0.0000E+00	0.0000E+00
6	6	0.0000E+00	0.0000E+00
7	7	0.0000E+00	0.0000E+00
8	8	0.0000E+00	0.0000E+00
9	9	0.0000E+00	0.0000E+00
10	10	0.0000E+00	0.0000E+00
11	11	0.0000E+00	0.0000E+00
12	12	0.0000E+00	0.0000E+00

[illegible]

PROGRAM CALLS TO ANALYZE
SCALE CALLS
1 3
2 3

PLANT	IMAGE
1. <i>Asplenium platyneuron</i> L. 2. <i>Asplenium adnigrum</i> L. 3. <i>Asplenium platyneuron</i> L. 4. <i>Asplenium adnigrum</i> L. 5. <i>Asplenium platyneuron</i> L. 6. <i>Asplenium adnigrum</i> L. 7. <i>Asplenium platyneuron</i> L. 8. <i>Asplenium adnigrum</i> L. 9. <i>Asplenium platyneuron</i> L. 10. <i>Asplenium adnigrum</i> L. 11. <i>Asplenium platyneuron</i> L. 12. <i>Asplenium adnigrum</i> L. 13. <i>Asplenium platyneuron</i> L. 14. <i>Asplenium adnigrum</i> L. 15. <i>Asplenium platyneuron</i> L. 16. <i>Asplenium adnigrum</i> L. 17. <i>Asplenium platyneuron</i> L. 18. <i>Asplenium adnigrum</i> L. 19. <i>Asplenium platyneuron</i> L. 20. <i>Asplenium adnigrum</i> L. 21. <i>Asplenium platyneuron</i> L. 22. <i>Asplenium adnigrum</i> L. 23. <i>Asplenium platyneuron</i> L. 24. <i>Asplenium adnigrum</i> L. 25. <i>Asplenium platyneuron</i> L. 26. <i>Asplenium adnigrum</i> L. 27. <i>Asplenium platyneuron</i> L. 28. <i>Asplenium adnigrum</i> L. 29. <i>Asplenium platyneuron</i> L. 30. <i>Asplenium adnigrum</i> L. 31. <i>Asplenium platyneuron</i> L. 32. <i>Asplenium adnigrum</i> L. 33. <i>Asplenium platyneuron</i> L. 34. <i>Asplenium adnigrum</i> L. 35. <i>Asplenium platyneuron</i> L. 36. <i>Asplenium adnigrum</i> L. 37. <i>Asplenium platyneuron</i> L. 38. <i>Asplenium adnigrum</i> L. 39. <i>Asplenium platyneuron</i> L. 40. <i>Asplenium adnigrum</i> L. 41. <i>Asplenium platyneuron</i> L. 42. <i>Asplenium adnigrum</i> L. 43. <i>Asplenium platyneuron</i> L. 44. <i>Asplenium adnigrum</i> L. 45. <i>Asplenium platyneuron</i> L. 46. <i>Asplenium adnigrum</i> L. 47. <i>Asplenium platyneuron</i> L. 48. <i>Asplenium adnigrum</i> L. 49. <i>Asplenium platyneuron</i> L. 50. <i>Asplenium adnigrum</i> L. 51. <i>Asplenium platyneuron</i> L. 52. <i>Asplenium adnigrum</i> L. 53. <i>Asplenium platyneuron</i> L. 54. <i>Asplenium adnigrum</i> L. 55. <i>Asplenium platyneuron</i> L. 56. <i>Asplenium adnigrum</i> L. 57. <i>Asplenium platyneuron</i> L. 58. <i>Asplenium adnigrum</i> L. 59. <i>Asplenium platyneuron</i> L. 60. <i>Asplenium adnigrum</i> L. 61. <i>Asplenium platyneuron</i> L. 62. <i>Asplenium adnigrum</i> L. 63. <i>Asplenium platyneuron</i> L. 64. <i>Asplenium adnigrum</i> L. 65. <i>Asplenium platyneuron</i> L. 66. <i>Asplenium adnigrum</i> L. 67. <i>Asplenium platyneuron</i> L. 68. <i>Asplenium adnigrum</i> L. 69. <i>Asplenium platyneuron</i> L. 70. <i>Asplenium adnigrum</i> L. 71. <i>Asplenium platyneuron</i> L. 72. <i>Asplenium adnigrum</i> L. 73. <i>Asplenium platyneuron</i> L. 74. <i>Asplenium adnigrum</i> L. 75. <i>Asplenium platyneuron</i> L. 76. <i>Asplenium adnigrum</i> L. 77. <i>Asplenium platyneuron</i> L. 78. <i>Asplenium adnigrum</i> L. 79. <i>Asplenium platyneuron</i> L. 80. <i>Asplenium adnigrum</i> L. 81. <i>Asplenium platyneuron</i> L. 82. <i>Asplenium adnigrum</i> L. 83. <i>Asplenium platyneuron</i> L. 84. <i>Asplenium adnigrum</i> L. 85. <i>Asplenium platyneuron</i> L. 86. <i>Asplenium adnigrum</i> L. 87. <i>Asplenium platyneuron</i> L. 88. <i>Asplenium adnigrum</i> L. 89. <i>Asplenium platyneuron</i> L. 90. <i>Asplenium adnigrum</i> L. 91. <i>Asplenium platyneuron</i> L. 92. <i>Asplenium adnigrum</i> L. 93. <i>Asplenium platyneuron</i> L. 94. <i>Asplenium adnigrum</i> L. 95. <i>Asplenium platyneuron</i> L. 96. <i>Asplenium adnigrum</i> L. 97. <i>Asplenium platyneuron</i> L. 98. <i>Asplenium adnigrum</i> L. 99. <i>Asplenium platyneuron</i> L. 100. <i>Asplenium adnigrum</i> L.	

347

[illegible][illegible]

GLOBAL VARIABLE NUMBER (FOR OBJECTIVE
MULTIPLIED INEQUALITY INDICATES MINIMIZATION) = -0.1000E+01

[illegible]

DESIGN VARIABLES

**HET N
ALTE
GEBU
VAN
LUTHER
KONINK**

100-443887-16

• • ESTIMATE DATA SUMARE RECLAMENTS

PE (VELOC) (MP)
A (TRAITS)

23514.5
23514.5

```

.....
      C C A M I N
.....
      FORTRAN PROGRAM FOR
.....
      CONSTRAINED FUNCTION MINIMIZATION
.....

```

INITIAL FUNCTION INFORMATION

```

OBJ = C.256313E+04
CE{JSICA VARIABLES (N-VECTOR)
C.10000E+01 0.13300E+01 0.10000E+01
CONSTRAINT VALUES (M-VECTOR)
C.4100E+00 -0.2041E+00 -0.3054E+02 -0.3920E+03 -C.50.00E+00 0.
C.4100E+02 -0.2447E+00 -0.3000E+00 0.3330E+03 -C.50.00E+01 0.

```

352

```

OPTIMIZATION RESULTS
OBJECTIVE FUNCTION 2      FUNCTION VALUE 0.10405E+03
GLOBAL LOCATION
DESIGN VARIABLES
ID   C1  V1  CUMUL  VAR  A2.  LOWER  VALUE  UPPER
1    1    1    0.000E+00  1    0.000E+00  0.1000E+01  0.1000E+01
2    2    1    0.000E+00  2    0.000E+00  0.000E+00  0.000E+00
3    3    1    0.000E+00  3    0.000E+00  0.000E+00  0.000E+00
DESIGN CONSTRAINTS
ID   CUMUL  VAR  NO.  LOWER  VALUE  UPPER
1    0.000E+00  1    1    0.000E+00  0.1000E+01  0.1000E+01
2    0.000E+00  2    1    0.000E+00  0.000E+00  0.000E+00
3    0.000E+00  3    1    0.000E+00  0.000E+00  0.000E+00

```

OPTIMIZATION RESULTS ----- DESIGN CASE NO. 3
SUBOPTIMUM "STRAIN"

DESIGN VARIABLES SPECIFIED: PE, VS, IN, DIA
ENVIRONMENTAL PARAMETERS: TIME (HRS) = 55.44000
DENSITY (LBS/SEC/FT³) = 0.12817000E-0
VELOCITY (FT/SEC) = 1.00000
WATER VIBRATION PRESSURE (PSIA) = 1.00000
WATER VIBRATION PRESSURE (PSIA) = 1.00000

DUAL PARAMETERS: TARGET CRACK COEFFICIENT = 1.1200
RELATIVE CRACK COEFFICIENT = 1.0000
NUMBER OF PROPELLERS = 1.00
DEPTH (FT) = 15.0000
DISPERSED STATE COEFFICIENT = 1.0000

PROPELLER PARAMETERS: NUMBER OF BLADES = 4
ALLOWABLE STRESS (PSI) = 24000.0
STEEL TYPE = STE

SELECTION VALUES: PE (PSI) = 1.0000
VS (LBS) = 1.0000
IN (IN) = 1.0000
DIA (IN) = 33.0000
ETAC SPECIFIED = 0.3394
J = 0.1000
K = 0.1000
L = 0.1000
M = 0.1000
N = 0.1000
O = 0.1000
P = 0.1000
Q = 0.1000
R = 0.1000
S = 0.1000
T = 0.1000
U = 0.1000
V = 0.1000
W = 0.1000
X = 0.1000
Y = 0.1000
Z = 0.1000
AA = 0.1000
BB = 0.1000
CC = 0.1000
DD = 0.1000
EE = 0.1000
FF = 0.1000
GG = 0.1000
HH = 0.1000
II = 0.1000
JJ = 0.1000
KK = 0.1000
LL = 0.1000
MM = 0.1000
NN = 0.1000
OO = 0.1000
PP = 0.1000
QQ = 0.1000
RR = 0.1000
SS = 0.1000
TT = 0.1000
UU = 0.1000
VV = 0.1000
WW = 0.1000
XX = 0.1000
YY = 0.1000
ZZ = 0.1000
AAA = 0.1000
BBB = 0.1000
CCC = 0.1000
DDD = 0.1000
EEE = 0.1000
FFF = 0.1000
GGG = 0.1000
HHH = 0.1000
III = 0.1000
JJJ = 0.1000
KKK = 0.1000
LLL = 0.1000
MMM = 0.1000
NNN = 0.1000
OOO = 0.1000
PPP = 0.1000
QQQ = 0.1000
RRR = 0.1000
SSS = 0.1000
TTT = 0.1000
UUU = 0.1000
VVV = 0.1000
WWW = 0.1000
XXX = 0.1000
YYY = 0.1000
ZZZ = 0.1000
AAAA = 0.1000
BBBB = 0.1000
CCCC = 0.1000
DDDD = 0.1000
EEEE = 0.1000
FFFF = 0.1000
GGGG = 0.1000
HHHH = 0.1000
IIII = 0.1000
JJJJ = 0.1000
KKKK = 0.1000
LLLL = 0.1000
MMMM = 0.1000
NNNN = 0.1000
OOOO = 0.1000
PPPP = 0.1000
QQQQ = 0.1000
RRRR = 0.1000
SSSS = 0.1000
TTTT = 0.1000
UUUU = 0.1000
VVVV = 0.1000
WWWW = 0.1000
XXXX = 0.1000
YYYY = 0.1000
ZZZZ = 0.1000
AAAAA = 0.1000
BBBBB = 0.1000
CCCCC = 0.1000
DDDDD = 0.1000
EEEEE = 0.1000
FFFFF = 0.1000
GGGGG = 0.1000
HHHHH = 0.1000
IIIII = 0.1000
JJJJJ = 0.1000
KKKKK = 0.1000
LLLLL = 0.1000
MMMMM = 0.1000
NNNNN = 0.1000
OOOOO = 0.1000
PPPPP = 0.1000
QQQQQ = 0.1000
RRRRR = 0.1000
SSSSS = 0.1000
TTTTT = 0.1000
UUUUU = 0.1000
VVVVV = 0.1000
WWWWW = 0.1000
XXXXX = 0.1000
YYYYY = 0.1000
ZZZZZ = 0.1000
AAAAA = 0.1000
BBBBB = 0.1000
CCCCC = 0.1000
DDDDD = 0.1000
EEEEE = 0.1000
FFFFF = 0.1000
GGGGG = 0.1000
HHHHH = 0.1000
IIIII = 0.1000
JJJJJ = 0.1000
KKKKK = 0.1000
LLLLL = 0.1000
MMMMM = 0.1000
NNNNN = 0.1000
OOOOO = 0.1000
PPPPP = 0.1000
QQQQQ = 0.1000
RRRRR = 0.1000
SSSSS = 0.1000
TTTTT = 0.1000
UUUUU = 0.1000
VVVVV = 0.1000
WWWWW = 0.1000
XXXXX = 0.1000
YYYYY = 0.1000
ZZZZZ = 0.1000

CONSTRAINT VALUES: MAX Q/A (FT) = 0.0000
MIN Q/A (FT) = 0.0000
V (IN/SEC) = 0.0000
PE (LBS/SEC) = 0.0000
VS (LBS) = 0.0000
IN (IN) = 0.0000
DIA (IN) = 0.0000
ETAC SPECIFIED = 0.3394
J = 0.1000
K = 0.1000
L = 0.1000
M = 0.1000
N = 0.1000
O = 0.1000
P = 0.1000
Q = 0.1000
R = 0.1000
S = 0.1000
T = 0.1000
U = 0.1000
V = 0.1000
W = 0.1000
X = 0.1000
Y = 0.1000
Z = 0.1000
AA = 0.1000
BB = 0.1000
CC = 0.1000
DD = 0.1000
EE = 0.1000
FF = 0.1000
GG = 0.1000
HH = 0.1000
II = 0.1000
JJ = 0.1000
KK = 0.1000
LL = 0.1000
MM = 0.1000
NN = 0.1000
OO = 0.1000
PP = 0.1000
QQ = 0.1000
RR = 0.1000
SS = 0.1000
TT = 0.1000
UU = 0.1000
VV = 0.1000
WW = 0.1000
XX = 0.1000
YY = 0.1000
ZZ = 0.1000
AAA = 0.1000
BBB = 0.1000
CCC = 0.1000
DDD = 0.1000
EEE = 0.1000
FFF = 0.1000
GGG = 0.1000
HHH = 0.1000
III = 0.1000
JJJ = 0.1000
KKK = 0.1000
LLL = 0.1000
MMM = 0.1000
NNN = 0.1000
OOO = 0.1000
PPP = 0.1000
QQQ = 0.1000
RRR = 0.1000
SSS = 0.1000
TTT = 0.1000
UUU = 0.1000
VVV = 0.1000
WWW = 0.1000
XXX = 0.1000
YYY = 0.1000
ZZZ = 0.1000
AAAA = 0.1000
BBBB = 0.1000
CCCC = 0.1000
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EEEE = 0.1000
FFFF = 0.1000
GGGG = 0.1000
HHHH = 0.1000
IIII = 0.1000
JJJJ = 0.1000
KKKK = 0.1000
LLLL = 0.1000
MMMM = 0.1000
NNNN = 0.1000
OOOO = 0.1000
PPPP = 0.1000
QQQQ = 0.1000
RRRR = 0.1000
SSSS = 0.1000
TTTT = 0.1000
UUUU = 0.1000
VVVV = 0.1000
WWWW = 0.1000
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YYYY = 0.1000
ZZZZ = 0.1000
AAAAA = 0.1000
BBBBB = 0.1000
CCCCC = 0.1000
DDDDD = 0.1000
EEEEE = 0.1000
FFFFF = 0.1000
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HHHHH = 0.1000
IIIII = 0.1000
JJJJJ = 0.1000
KKKKK = 0.1000
LLLLL = 0.1000
MMMMM = 0.1000
NNNNN = 0.1000
OOOOO = 0.1000
PPPPP = 0.1000
QQQQQ = 0.1000
RRRRR = 0.1000
SSSSS = 0.1000
TTTTT = 0.1000
UUUUU = 0.1000
VVVVV = 0.1000
WWWWW = 0.1000
XXXXX = 0.1000
YYYYY = 0.1000
ZZZZZ = 0.1000

PROPELLER "FCINTS": MAX Q/A (FT) = 0.0000
MIN Q/A (FT) = 0.0000
V (IN/SEC) = 0.0000
PE (LBS/SEC) = 0.0000
VS (LBS) = 0.0000
IN (IN) = 0.0000
DIA (IN) = 0.0000
ETAC SPECIFIED = 0.3394
J = 0.1000
K = 0.1000
L = 0.1000
M = 0.1000
N = 0.1000
O = 0.1000
P = 0.1000
Q = 0.1000
R = 0.1000
S = 0.1000
T = 0.1000
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V = 0.1000
W = 0.1000
X = 0.1000
Y = 0.1000
Z = 0.1000
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FF = 0.1000
GG = 0.1000
HH = 0.1000
II = 0.1000
JJ = 0.1000
KK = 0.1000
LL = 0.1000
MM = 0.1000
NN = 0.1000
OO = 0.1000
PP = 0.1000
QQ = 0.1000
RR = 0.1000
SS = 0.1000
TT = 0.1000
UU = 0.1000
VV = 0.1000
WW = 0.1000
XX = 0.1000
YY = 0.1000
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CCC = 0.1000
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EEE = 0.1000
FFF = 0.1000
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VVVVV = 0.1000
WWWWW = 0.1000
XXXXX = 0.1000
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ZZZZZ = 0.1000

PROGRAM CALLS TO ANALYZE
SCALE CALLS
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10. Dr. William B. Morgan 1
David W. Taylor Naval Ship Research
& Development Center
Ship Performance Department (Code 15)
Bethesda, Maryland 20084
11. Dr. Young T. Shen 1
David W. Taylor Naval Ship Research
& Development Center
Ship Performance Department
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