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Procedures are presented whereby natural vibration and transient response analyses of partially submerged, supercavitating marine propellers may be calculated by means of a standard NASTRAN structural analysis program. The use of these procedures was demonstrated by analyses of an existing propeller, for which some experimental data were available. Results were comparable only in a limited way, but peak calculated dynamic stresses were of

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apparently more than twice the magnitude of equivalent static stresses.

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ABSTRACT

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means of a standard NASTRAN structural analysis program.
The use of these procedures was demonstrated by analyses
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ADMINISTRATIVE INFORMATION

INTRODUCTION

The utilization of high speed marine vehicles by the United States

Navy has created a need for an improved structural analysis and design

capability for high speed propulsors. These are generally supercavitating

propellers, which may also be partially submerged. In their hydrodynamic

performance and structural integrity, these propellers, because of their

different geometries and modes of operation, represent substantial depar-

ture from conventional propellers, for which a large body of experience

exists. Dynamic aspects of structural response, in particular, are ex-

pected to be more significant for these propellers. These aspects need to

be evaluated so that attempts to attain optimum hydrodynamic designs will not be limited unnecessarily by structural considerations. An effort was therefore instituted to develop methods of predicting dynamic stress and deflection behavior of high speed propellers under realistic time-dependent loading conditions.

A preliminary investigation indicated that meaningful results were not likely to be obtained other than by computer studies. Various computer programs have been used to calculate the full vibration modes and frequencies of completely submerged propellers, but until recently the effect of immersion in water has been accounted for by assuming that a more or less arbitrary mass of fluid is attached to the propeller blade. This "added effective mass" approach, which incorporates the assumption that the fluid is incompressible, is considered to account adequately for fluid structure interaction in most vibration and transient response problems, provided valid added fluid mass terms can be obtained. A few investigators have recently published descriptions of analyses of dynamic behavior of submerged structures in which effects of submergence in water are computed on a rational basis. One such investigation[1]* yielded a procedure by which the existing NASTRAN finite element structural analysis program could be applied to the submerged structure problem, even without making the incompressibility assumption. That work forms the basis of the analyses described here. The approach was selected because of the availability of NASTRAN at DTNSRDC and because of its flexibility of application.

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*A complete listing of references is given on page 57.

Further modifications were made to this procedure to adapt it to the general problem of predicting free vibration frequencies and transient response of supercavitating, partially submerged propellers. The resulting approach was applied to determine natural frequencies of two propellers, and the dynamic stress response of one propeller for which some experimental data were available. Only a limited comparison of results was possible; however, the calculated frequencies and dynamic stresses appeared to be reasonable. The dynamic analysis and its application via NASTRAN are described in this report.

DESCRIPTION OF ANALYSIS

In the analysis to be used here, the fluid surrounding the submerged structure, in this case an individual propeller blade, is represented by a finite element idealization. More precisely, a quantity of fluid sufficiently large that its effect on the structure should nearly be the same as that of an infinite quantity is represented. The theory governing this approach is described by Zienkiewicz.[2] A concise presentation, with a delineation of the strategy of application by means of existing NASTRAN capabilities is given by Everstine et al.[1] The theory and application procedure will be briefly summarized here.

Conventional analytical techniques lead to the following matrix equation, which describes the dynamic behavior of the propeller blade when represented in finite element form:

$$[M]\{\ddot{u}\} + [K]\{u\} = \{F\} + [L]\{\bar{p}\} \tag{1}$$

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where $\{u\}$ is the set of unknown grid point displacements and $\{F\}$ is a set of applied time-dependent forces. The column matrix $\{\bar{p}\}$ is the set of unknown pressures on the fluid-structure interface grid points. The last term, $[L]\{p\}$, represents the fluid loading on the structure.

The set of unknown pressures at all the grid points of the fluid finite element idealization is represented in the following matrix equation:

$$[Q]\{\ddot{p}\} + [H]\{p\} = - [S]\{\bar{\ddot{u}}\} \qquad (2)$$

The last term in Equation (2) represents the effect of accelerations of the structural grid points at the fluid structure interface on the pressures in the fluid. The bar placed over $\{u\}$ indicates that only normal interface deflections are involved in that term. The fluid may be considered an acoustic medium, in which case Equation (2) provides a valid description of its dynamic behavior if it actually represents the wave equation

$$\nabla^2 p = \frac{1}{c^2} \ddot{p} \qquad (3)$$

with appropriate boundary conditions. In Equation (3), c represents the speed of sound in the fluid. It was shown previously[1] that the implementation of the procedure can be accomplished by means of a standard structural program. The left side of Equation (2) is treated as being analogous to the left side of Equation (1), i.e., it is treated as a dynamics problem with unknown variables $\{\dot{p}\}$. Only one translational degree of freedom at each grid point of the fluid is left unconstrained, however, and that one remaining component is interpreted as pressure. In addition, all degrees of freedom may be constrained on the outer fluid boundary (all boundary

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points not in contact with the moveable structure). Finally for the three-dimensional case, the following material property matrix, representing Hooke's law, is used:

$$\left\{\begin{array}{c} \sigma_{xx} \\ \sigma_{yy} \\ \sigma_{zz} \\ \sigma_{xy} \\ \sigma_{yz} \\ \sigma_{xz} \end{array}\right\} + \begin{bmatrix} 1 & -1 & -1 & 0 & 0 & 0 \\ -1 & 1 & -1 & 0 & 0 & 0 \\ -1 & -1 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \left\{\begin{array}{c} u,_x \\ v,_y \\ w,_z \\ u,_y + v,_x \\ v,_z + w,_y \\ w,_x + u,_z \end{array}\right\} \qquad (4)$$

With the NASTRAN program, it is not usually necessary to input the matrix (4). As pointed out by Everstine,[3] the same information can be input by specifying an isotropic material with the following values:

> Shear modulus $G = 1.0$
>
> Poissons ratio ν is not input (so the program will
>
> compute a value).
>
> Young's modulus $E = \alpha G$; $\alpha \gg 1.0$

Here, $\alpha + 1.0$ should be numerically indistinguishable from α. On most computers, $\alpha = 10^{20}$ will suffice. Equations (1) and (2) may now be combined into one set:

$$\begin{bmatrix} M & 0 \\ S & Q \end{bmatrix} \left\{\begin{array}{c} \ddot{u} \\ \ddot{p} \end{array}\right\} + \begin{bmatrix} K & -L \\ 0 & H \end{bmatrix} \left\{\begin{array}{c} u \\ p \end{array}\right\} = \left\{\begin{array}{c} F \\ 0 \end{array}\right\} \qquad (5)$$

A dynamic problem governed by Equation (5) can be run (the free vibration mode analysis results from letting F be null) by providing finite element data for both structure and fluid, in which case all matrices except

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S and L in Equation (5) will be set up automatically. Note that grid points for structure and fluid, including those on the interface which have the same coordinates, are numbered separately. Thus, the only coupling between fluid and structure is provided by the off-diagonal matrices, S and L. Equation (1), which expresses a balance of forces, shows that L relates the pressure at the fluid-structure interface to force resulting from that pressure. In a lumped formulation, the terms of L may be taken to be the interface surface areas associated with each fluid-structure interface grid point. In general, there will be three areas for each grid point - one for each coordinate direction. Zienkiewicz[2] has shown that

$$S = \rho L^T \tag{6}$$

Equation (5) then becomes

$$
\begin{bmatrix} M & 0 \\ \rho L^T & Q \end{bmatrix}
\begin{Bmatrix} \ddot{u} \\ \ddot{p} \end{Bmatrix}
+
\begin{bmatrix} K & -L \\ 0 & H \end{bmatrix}
\begin{Bmatrix} u \\ p \end{Bmatrix}
=
\begin{Bmatrix} F \\ 0 \end{Bmatrix}
\tag{7}
$$

The L and L^T matrices may be determined separately and input directly, using the DMIG option of NASTRAN. Thus, formulation of Equation (7) (or Equation (5)) is completed, and the solution is carried out by the program. However, the presence of the off-diagonal matrices destroys the symmetry of the mass and stiffness matrices, requiring the use of time-consuming complex eigenvalue routines in the solution of these equations.

The natural vibration frequencies for some flat plates with varying levels of immersion were calculated by the method described and compared

with experimental results by Marcus.[4] Good agreement was obtained when a

sufficient amount of water was modeled, and in fact the results provide

a useful reference for judging the size of a fluid mass required to repre-

sent an infinite body of water.

APPLICATION TO PROPELLER BLADES

It was planned originally to apply the analysis as represented by

Equation (7) to a supercavitating propeller blade, P3604, for which data

for a finite element idealization were available from a previous stress

study. The idealization consisted of 155 grid points and 16 quadratic

isoparametric, twenty-noded, three-dimensional elements (NASTRAN data card

CIHEX2). The purpose of this sample calculation was to verify that appli-

cation of this procedure to the more complicated propeller blade would be

feasible. It was apparent, however, that the cost of such a computer run

could be high. A fluid idealization was constructed of only three layers

of elements and extended one element beyond the edges of the blade. The

fluid idealization, which was thought to be just large enough to represent

an infinite quantity, but only on one side of the blade, contained 90

three-dimensional elements and 578 grid points. A total of 263 uncon-

strained degrees of freedom resulted, and this number would be about

doubled for fluid on both sides of the blade. The blade itself was con-

sidered fixed along its base, so that a total of 396 degrees of freedom

(3 for each unconstrained grid point) remained. The total number of

degrees of freedom for fluid and structure thus led to mass and stiffness

matrices for Equation (7) of order 659. Eigenvalue extraction of these

large unsymmetrical matrices would have required a time-consuming complex

extraction routine. It was decided, therefore, to attempt to reduce the

computer effort required without any significant sacrifice of accuracy.

In Equations (2) and (7), the Q matrices, which contain a factor of 1/c, represent the effect of compressibility of the fluid. This effect is not considered significant except for high frequencies or in confined fluid spaces. Most analyses, including that of Everstine,[1] have incorporated the simplifying assumption of incompressibility; as a result, 1/c, and hence Q, are zero. This assumption was not included in the formulation of Equation (7), which was set up for ready computer application, because there was little advantage in doing so.

When Q is taken to be zero, Equation (7) is readily reduced to

$$[M + \rho L H^{-1} L^T]\{\ddot{u}\} + [K]\{u\} = \{F\} \tag{8}$$

One additional significant operation, that of obtaining the inverse of H, is required to set up Equation (8). However, this and the eigenvalue extraction operations are performed on matrices about one-half the size of those of Equation (7). Furthermore, the matrices of Equation (8) are symmetrical. The term $\rho L H^{-1} L^T$ is interpreted as the added effective mass of the fluid. It is clear that fluid on only one side of the propeller blade may be idealized, and the added mass term can be made to represent fluid on both surfaces by using a value for fluid density, ρ, that is double the actual value.

No standard NASTRAN solution option, or "rigid format," is available to formulate and solve Equation (8). Executive modules can be manipulated, however, though the Direct Matrix Abstraction Program (DMAP) capability, and existing rigid formats may be altered in the same way. These capabilities were used to devise a procedure for implementing Equation (8).

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First, the fluid matrix (or rather, $(1/\rho)H$) was computed and made available for later reference. This fluid "stiffness" matrix was produced by making a static stress run on the fluid mass with material properties and boundary conditions as discussed above. ASET1 cards were used to specify that the solution set be retained only at the interface grid points, and an "OUTPUT1" DMAP ALTER instruction to specify that the resulting condensed stiffness matrix (or H) be saved on a permanent file. Another ALTER instruction was used to stop further execution of the problem. This run can also be used to obtain terms of the L matrix. It was suggested previously that areas associated with each structural interface grid point can be used as L matrix terms. Calculating these areas and obtaining their projections in the three coordinate directions for a propeller surface can be quite difficult. It is much easier, and equivalent, to specify a unit pressure loading on the interface and request a printout of the three equivalent nodal forces on these grid points. The forces will thus be calculated in a consistent manner. These forces can be used to make up the L matrix. They are functions of only the pressurized surface shape and the location of the grid points. Therefore, since these two quantities are identical for both the structure and the fluid at their interface, the unit pressure load can be applied to the idealized fluid interface in the same run from which the H matrix is obtained. The equivalent nodal forces can then be entered on DMIG cards as L matrix terms. Since the fluid run has only one degree of freedom, while all three translational degrees are needed to obtain the three components for each surface grid point, the equivalent force matrix must be printed out before constraints are applied. This printout is requested through another ALTER instruction.

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To summarize the procedure: a static stress run is started on the fluid mass with unit pressure applied to the interface. All interface grid points are specified on ASET1 cards. The stiffness matrix (after constraints and condensation are applied) is placed on a permanent file via the required control card. An OUTPUT1 ALTER instruction and the equivalent nodal forces are then printed out, at which point the calculation is stopped. The matrix condensation is not theoretically required, but is done to save space; it does not affect the final results.

Equation (8) may be set up for the propeller and solved to obtain either the frequency response or the dynamic response to applied time-dependent forces by running the propeller data with the additional data already obtained. The natural frequencies are obtained by specifying a modified natural modes calculation with F null (Rigid Format 3); the dynamic response is obtained by specifying a transient response calculation with F input (Rigid Format 9). Each of these rigid formats requires its own ALTER routine, although each routine works in essentially the same way, and the additional input is handled similarly. Structural grid point data must include one extra scalar point (SPOINT) for each fluid interface grid point listed on ASET1 cards and thus retained as a degree of freedom in the H matrix calculation. These scalar points are dummy grid points which have no coordinates, but have one allowable degree of freedom each (the zero component). They are established by listing their identification numbers on SPOINT cards. These identification numbers are (for convenience) the fluid interface grid point numbers, and they must be different from all propeller grid point numbers. The purpose of the scalar points is to expand the dimensions of the structural stiffness matrix, before

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constraints are applied, sufficiently to accept the L (or L^T) matrix which is also input to the stiffness matrix via DMIG cards. It was found more advantageous to require the L^T matrix; the L matrix can readily be derived from it by transposition. The terms of the L^T matrix are specified on DMIG cards, each of which relates one of the three nodal force components per unit pressure at a wetted propeller grid point, obtained from the fluid calculation with the zero component of the corresonding scalar point. If the algebraic signs of all of the L^T terms are reversed, those of L will also be reversed, and the added mass term, $\rho LH^{-1}L^T$, will be unchanged; therefore a sign error for the L^T matrix as a whole has no effect. Since only the interface fluid points are input here (as scalar points), the zero rows of L are eliminated so that the matrix conforms with the condensed version of H^{-1}. The $(1/\rho)H$ matrix is obtained from the file on which it has been stored by including the required control card and an *INPUTT1 ALTER* instruction.

Two partitioning matrices, named PVEC1 and PVECD1, must also be input via DMI cards. These are column matrices having the dimensions $(N+S)\times 1$. N is the total number of structural degrees of freedom (number of grid points x6) and S is the number of scalar points. For PVEC1, the first N terms are zero, and the remaining S terms are 1.0. PVEC1 is used to partition the stiffness matrix to obtain L^T, used with $(1/\rho)H$ by the ALTER routine to form the added mass term $\rho LH^{-1}L^T$, which is then added to the structural mass matrix. Note that the inverse of $(1/\rho)H$ is ρH^{-1}. For the PVEDC1 matrix, all (N+S) terms are zero. PVECD1 is used to form a "dummy" partition on the "augmented" mass matrix, which now includes the added mass terms, so that the program will correctly perceive this matrix as symmetrical.

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One final type of additional input is required: all scalar points must be listed on single point constraint (SPC) cards. These constraints are in addition to whatever constraints are applied to the propeller. It is suggested that 20-node three-dimensional CIHEX2 elements, with two integration points specified, be used to represent both the fluid and the propeller, and that the consistent mass matrix formulation be specified for the propeller.

The procedure just described can be used to obtain vibration modes and dynamic response of propellers under a variety of conditions of submergence. Partial submergence at any given instant can be represented during a fluid run by listing on ASET1 cards only the fluid grid points which correspond to submerged points on the propeller. During a structural run these points are listed on SPOINT cards. Also, the dimensions of the PVEC1 and PVECD1 column matrices must be adjusted by making the number of terms with value of 1.0 at the end of the PVEC1 column equal to the number of wetted grid points. Wetting of both surfaces of the blade is simulated by using double the actual value of fluid density, ρ, for the fluid run. Wetting of only one surface, such as occurs during supercavitation, is represented by use of the actual value of ρ.

This procedure can be extended, without further DMAP program modifications, to analyze dynamic response of partially submerged propellers and to take into account the progressively changing degree of submergence. The extended procedure consists essentially of running the analysis in separate steps, one for each arbitrarily chosen stage of submergence. A convenient way to determine a new stage of submergence is to consider the wetting of a new row of propeller elements. This extended procedure was

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devised and was applied to an existing propeller for which some experimental and analytical data were available. The details of this application will be presented later. The finite element idealization of this blade was laid out so that one series of element boundaries coincided with water lines on the propeller blades as it progressed into the water during each revolution. There were two such boundaries in this rather coarse idealization, defining three rows of elements; hence, three stages of submergence were assumed.

The fluid run, to obtain the condensed $(1/\rho)H$ matrix, was run once for each stage of submergence. For each run, the solution set of wetted grid points, as defined by ASET1 cards, contained only the points presently wetted, i.e., points just submerged plus all points previously submerged. Similarly, unit pressure was applied to the corresponding wetted element faces to obtain the L^T matrix terms for the same wetted points. Finally, those interface grid points not yet submerged had to be considered part of the fluid boundary and were constrained. Constraints were, of course, removed from those points as they became submerged in subsequent stages and added to those included on ASET1 cards. Each of the $(1/\rho)H$ matrices thus produced and stored on a permanent file was assigned a separate name; in this case the names used were HMATRIXSTEP1, HMATRIXSTEP2, and HMATRIXSTEP3. Such separate identification of the L^T matrices was not necessary, as they are manually punched on DMIG cards and input separately to the structural computer runs. The structural run in this case was also carried out once for each stage of submergence, but all except the first were restart runs. Thus, all but the last run was checkpointed.

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The series of runs is set up as follows. First, time-dependent forces are specified for the selected grid points by means of the required DAREA, DLOAD, TABLED1, and TLOAD1 cards. The time spanned by these forces covers the entire time for which the analysis is applied. The time at which the force is initiated at each selected grid point is dictated by the speed of rotation of the propeller and by the location of the point. The user must also specify the length of each integration time step, and the number of steps, on a TSTEP card. The calculation is terminated when the time defined by the product of time step x number of steps on the TSTEP card has elapsed. If a uniform time step is used throughout, the number of steps may be specified to make each run cover just the length of time required for the water line to progress from the first to the second boundary defining the present stage of submergence. The first run and each restart then require a different TSTEP card (unless, by coincidence, each stage of submergence lasts the same length of time). Other changes must also be made between runs. Scalar points for all interface fluid grid points which are to be wetted at any time during the analysis must be input (on SPOINT cards) for the first run, and this does not change for succeeding restarts. The same is true of the scalar point constraints. The PVECD1 matrix is also input as before, with column dimension equal to six times the number of propeller grid points plus the number of scalar points, and it is not changed. The PVEC1 column matrix is now replaced by a series of matrices, one for each structural run, and they may be designated PVEC1, PVEC2, and PVEC3. The column dimension is the same for all of these, and is the same as that of PVECD1. The number and location of the "1.0" terms, however, must correspond to the total set of wetted

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The series of runs is set up as follows. First, time-dependent forces are specified for the selected grid points by means of the required DAREA, DLOAD, TABLED1, and TLOADi cards. The time spanned by these forces covers the entire time for which the analysis is applied. The time at which the force is initiated at each selected grid point is dictated by the speed of rotation of the propeller and by the location of the point. The user must also specify the length of each integration time step, and the number of steps, on a TSTEP card. The calculation is terminated when the time defined by the product of time step x number of steps on the TSTEP card has elapsed. If a uniform time step is used throughout, the number of steps may be specified to make each run cover just the length of time required for the water line to progress from the first to the second boundary defining the present stage of submergence. The first run and each restart then require a different TSTEP card (unless, by coincidence, each stage of submergence lasts the same length of time). Other changes must also be made between runs. Scalar points for all interface fluid grid points which are to be wetted at any time during the analysis must be input (on SPOINT cards) for the first run, and this does not change for succeeding restarts. The same is true of the scalar point constraints. The PVECD1 matrix is also input as before, with column dimension equal to six times the number of propeller grid points plus the number of scalar points, and it is not changed. The PVEC1 column matrix is now replaced by a series of matrices, one for each structural run, and they may be designated PVEC1, PVEC2, and PVEC3. The column dimension is the same for all of these, and is the same as that of PVECD1. The number and location of the "1.0" terms, however, must correspond to the total set of wetted

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interface points as represented by the scalar points during each run. The DMAP ALTER instruction which utilized PVEC must also be changed from run to run to call for the currently available PVECi matrix. Another ALTER instruction, as well as a control card, must be changed for each run to obtain the required $(1/\rho)H$ matrix for each stage. Finally, each run must also have a new L^T matrix input via DMIG cards. Since this information is part of the bulk data, the previous L^T matrix must be eliminated during each restart.

Sample input for a vibration problem and for a transient response problem are presented in the appendix.

VIBRATION ANALYSIS OF P3604 PROPELLER

The vibration analysis procedure was first applied to a supercavitating propeller, P3604, for which finite element idealization data were already available from a previous stress study. The blade was divided into 16 isoparametric, 20-noded, three-dimensional elements, with 155 grid points (Figure 1). A quantity of water three elements thick, extending one element beyond the edges of the blade, and generally following the twist of the blade, was assumed. The elements were roughly cubical, and the thickness of the water modeled was about one-half to two-thirds the length of the blade. This size was judged to be sufficient to represent an infinite body of water, based on a study of the results presented by Marcus.[4] With the procedure used here, larger representations could be investigated at fairly moderate cost. The double value of water density was input to represent water on both sides of the blade. This fluid idealization consisted of 578 grid points and 90 elements. A total of 263 degrees of freedom remained after constraints were applied. The fluid-structure

interface surface contained 65 grid points, which were retained in the
H matrix. The L^T matrix terms numbered 65x3 or 195. However, nine of
the interface points were adjacent to the base grid points of the propeller,
which were later to be constrained. The corresponding 9x3, or 27 L^T matrix
terms were therefore not included on DMIG cards. Space was later reserved
for them in the propeller matrices, however, as 65 scalar points were
input, but the L^T boundary terms which were not input were implicitly zero.
It was not necessary to leave out these terms; they would be eliminated
later by constraints. With this procedure, the pressures in the water at
the nine base grid points were not constrained to zero, even though deflec-
tions of the corresponding propeller grid points were constrained. The
five lowest natural frequencies of the blade in water were calculated and
are presented, with the corresonding calculated in-air frequencies, in
Table 1. The modal deflection data indicated that the first mode of
vibration consisted of nearly pure spanwise bending, while the other modes
contained a combination of torsion and chordwise bending. Although no
experimental data exist to compare with this sample calculation, the
results appear to be consistent with experimental results for more conven-
tional blades, particularly for the first mode. It seems rather remarkable
that the ratios of frequencies in water to those in air are fairly constant,
ranging from 0.46 to 0.55, for all modes. This was not expected because
of the large differences in thickness of the blade and the variety of
possible vibration modes. This phenomenon may not be characteristic of
other blade geometries.

The version of NASTRAN used for these analyses was Level 17. Proce-
dures for both the vibration and transient analyses are listed in the
Appendix.

TRANSIENT RESPONSE ANALYSIS OF SES-100B PROPELLER

After this work was underway, some full scale test results, including both vibration and transient response data, became available[5,6] for the SES-100B controllable pitch, partially submerged, supercavitating propeller (number 7016.3). Allison's work[5] also contains finite element analyses of the vibration modes and transient response of this blade, utilizing 276 grid points and 279 plate bending elements. Calculated transient forces were used, and a constant physical mass of water of approximately conical shape circumscribing the blade, was taken as added effective mass. One-half of the imaginary cone of water was actually used to simulate full cavitation. Transient response, in the form of measured stresses at a gage near the root of the blade, was plotted versus time for the period during which the blade enters the water and reaches maximum submergence.

The SES-100B propeller was selected for this transient response analysis because of the availability of geometrical and test data. Due to the developmental nature of this application, however, and to time and cost constraints, the idealization constructed was rather coarse, consisting of 96 grid points and nine CIHEX2 isoparametric three-dimensional elements. A detailed study of this blade would require a finer idealization, particularly so because it contained an annex, or discontinuity, in the pressure surface curvature. The exercise of engineering judgment attempted to compensate for this coarseness in constructing the idealization, in which, for instance, thicknesses at grid points do not all coincide exactly with those on the actual blade. One of the constraints on placement of element boundaries was to require that one set of boundaries coincide with water

lines at successive assumed stages of submergence of the blade. This constraint would not be necessary with a fine idealization.

A view of the blade, looking in the forward direction, is shown in Figure 1. A series of water lines at various stages of submergence was constructed from data reported by Lewis[6] and drawn on Figure 1. An idealization was constructed with two of the element boundaries approximately coinciding with two water lines, and this is shown in Figures 2 and 3. In these figures the water lines are shown slightly curved because the view of the propeller is flattened. The location of the strain gage from which Allison's transient response data[5] were obtained is also shown in Figure 2. For the first arbitrarily-defined stage of submergence, elements 7 through 9 are submerged; for the second stage, elements 4 through 9 are submerged; and for the third stage, all elements are submerged. The fluid mass idealized for this case was of approximately the same size and shape relative to the blade as for the P3604 vibration analysis, but the fluid for the SES-100B was divided into only two layers. An outline of one face of the fluid mass, showing the fluid-structure interface, is shown in Figure 4. The entire fluid mass is shown in Figure 5.

The operating conditions for which this calculation was carried out were the design conditions of 85 knots, 1870 rpm, and 33-degree blade pitch. Blade pressures are discussed by Allison[5] and Lewis,[6] both of whom considered the pressure at each point to be applied in three stages. First was an impact pressure, computed according to a theory by Pierson,[7] followed by an entry pressure predicted from a theory by Wang.[8] Finally, a steady value was reached, the value predicted from a theory by Yim. The same procedure was followed here to calculate forces to apply to grid

points 73, 75, 47, 49, 21, and 23. These are mid-side nodes and are so situated that force is applied to each when the propeller reaches the mid-point of its stage of submergence. The pressure versus time plot at each of these grid points was derived from data given by Lewis.[6] These plots are presented in Figure 6 and show that these are essentially pulse pressures with no oscillating component.

The transient response analysis consisted of one fluid and one pro-peller computer run for each stage of submergence, a total of six runs. Stresses are printed out in NASTRAN at the grid points and at the element centroids. Unfortunately, it was not feasible to place a grid point exactly where experimental data were available. Therefore, stresses computed at three grid points (22, 36, and 39) which surround this point (shown as Gage 1 in Figure 2) were plotted and the plots are shown in Figures 7, 8, and 9. Static stresses were also calculated and plotted on these same figures. The three portions of the dynamic forces were averaged and applied at the same points to obtain these static stresses. The dyna-mic pressures were also applied, but with the steady state value truncated, to the propeller in air, and the results are given in Figures 10, 11, and 12. The plot of dynamic stresses, reproduced from Allison's paper,[5] is presented here as Figure 13. Natural vibration frequencies for the SES-100B propeller at the three stages of submergence were also calculated and are presented in Table 2.

DISCUSSION OF SES-100B ANALYSIS RESULTS

The primary purpose of this analysis was to verify the computational procedures developed and to produce results that appear reasonable and that provide some insight into the behavior of such propellers. It was also

desired that, despite the coarseness of the idealization, some meaningful comparisons could be made with experimental data.

The plots of transient stresses in the propeller in water (Figures 7, 8, and 9) show that the peak stresses at the three locations plotted range from 21500 to 32000 psi. The measured peak stress shown in Figure 13 is about 31000 psi. This apparent close agreement is probably fortuitous. The stress amplitudes shown in the analytical plots vary with a predominant frequency equal to the lowest natural frequency of the propeller, as verified by the natural frequency analysis. What appears to be a similar predominant vibrational component, with nearly the same frequency, is displayed in the experimental plot (Figure 13). Substantial amplitude damping is evident in the experimental plot, however, even within each complete period of vibration.[*] Both the analytical and experimental plots indicate that the blade vibrates through several complete cycles before becoming fully submerged. Thus, pressure due to submergence in the later stages are applied when the existing calculated amplitudes of deflection are in error, due to the lack of damping. Furthermore, the calculated phase could be in error due to the probable slight inaccuracy of the calculated natural frequencies. Calculated response due to these later water entry pressures may therefore detract from, rather than improve, accuracy of the overall dynamic response. The calculated stress-time plots show no apparent reaction to these later stage pressures, however. This is evidently because the last part of the propeller to enter the water is the portion close to the hub where lower pressures are generated at impact (due to the smaller

---

*Damping was not accounted for in the analysis, but could be, as discussed later.

radii and hence lower linear velocity resulting from rotation) and impact pressures produce smaller bending moments due to the smaller effective moment arms. The plot of calculated stress versus time is probably meaningful quantitatively only to the first peak if damping is not accounted for. Fortunately, this portion of the curve, or more particularly the value of this peak, is of primary interest.

Two other features of these curves are significant. First, peak stress values are practically the same for the in-water and the in-air cases. Second, these peak values are on the order of two to three times the static values. This suggests that, for this approximately pulse-type pressure application, the blade behaves somewhat like a weight suddenly suspended by a spring: the weight oscillates about the static equilibrium point with an amplitude double the static deflection. However, the ratios of the dynamic to static stresses in the propeller blade probably vary at different locations because of the complicated shape. For this particular example, a Fourier series representation of the assumed pressure pulses apparently would not contain any strong components near any of the natural frequencies in water or in air. The damping effect of water no doubt serves to decrease peak dynamic stresses slightly, but the main effect of submersion in water, apart from transmitting force to the blade, appears to be in altering its natural frequencies. If a detailed study of a propeller were to be made, it would probably be wise to obtain stresses at all grid points (at least all the points on one surface) because a resonance magnification might occur locally, and hardly show up at the root of the blade.

The fundamental, or lowest, natural frequencies of the blade in air and in water may be derived from the stress versus time plots since the time record is probably long enough. All three plots for the in-air case display frequencies of about 650 Hz, slightly higher than the calculated natural frequency of 624 Hz shown in Table 2. The plots indicate that in water the blade rings at a fairly constant frequency of about 510 Hz, which is close to the natural frequency of 574 Hz calculated for the blade under its first stage of submergence. During most of the time covered by the plots, however, the blade is fully submerged, and one would expect the frequency to fall to about 420 Hz. A smaller initial stage of submersion, for which the fundamental frequency is higher, might produce a correspondingly higher ringing frequency. In this case, however, the initial load would also be smaller, being applied to the smaller area of the blade, and might not predominate as it does in the present case.

Damping (either hydrodynamic or structural) could readily be accounted for in this analysis, but the values of damping terms would have to be determined by the user, probably empirically. All damping would be accounted for in the structural computations. Since damping terms can be derived from the relative amplitudes of successive cycles of a freely vibrating structure, plots such as Figure 13, in which the attenuation of amplitude after initial response is clearly illustrated, could probably be used for this purpose. The principal effect of damping on peak calculated stresses would probably occur when two or more substantial dynamic forces are applied, separated by time intervals of the order of one-half a fundamental period.

It would be pointless to carry the analysis further in time to cover the emergence of the blade from the water, since the dynamic forces applied at that time would result essentially from releasing the relatively small steady state submergence pressures. These forces would be much less severe than those at entry.

It has been assumed in this analysis that dynamic behavior of a propeller can be adequately described by analysis of a single blade, fixed along its base. Errors due to this assumption may be significant in some cases, particularly for propellers without relatively massive hubs. The errors could be introduced in two ways. First, flexibility of the hub violates the assumption of complete fixity, leading to lower natural frequencies than calculated. This effect was noted by Allison[5] in connection with the SES-100B propeller and with tests of a single blade mounted in a test jig. Second, hub flexibility and lack of great mass may permit a significant degree of dynamic interaction among the blades. It is also possible that in some cases significant interaction may occur through the water between the blades.

The computational procedures followed here could no doubt be simplified and automated to some extent with the aid of further executive module programming.

CONCLUSIONS

1. Rational procedures have been presented for calculating the natural vibration modes and transient response of partially or fully submerged, supercavitating or conventional marine propellers. Cost of these analyses should be moderate, and they require only use of a standard NASTRAN program.

2. Both the vibration modes and the transient response analyses, particularly when progressive submergence is treated, need more verification.

3. For the essentially pulse-shaped pressure-time profile, as used here in the SES-100B propeller example, peak root stresses were predicted equally well whether the blade was considered in air or in water. This may not have been true of stresses elsewhere on the blade. Also, it may have been by chance that no resonances of the blade were excited by components of the assumed pressures. If time-dependent pressures with oscillatory components were applied, it is expected that peak stresses would be affected by submergence in water.

4. Calculated stresses indicated, as did published experimental results, that blade root stresses due to pulse pressures can be two or more times as high as calculated stresses based on the same pressures applied statically.

5. Detailed studies of stresses and deflections throughout typical propeller blades, utilizing finer finite element meshes would be useful in providing more information about response of typical propellers under various conditions.

6. When damping was not taken into account, transient response after about the first half of a fundamental vibration period was quite unrealistic, but peak stress values were apparently not affected. Damping constants need to be established, perhaps through an empirical approach. The apparent failure of the blade ringing frequency to fall promptly to the fully submerged value needs further investigation.

7. It would be worthwhile to simplify and automate, whenever possible, the procedures used here.

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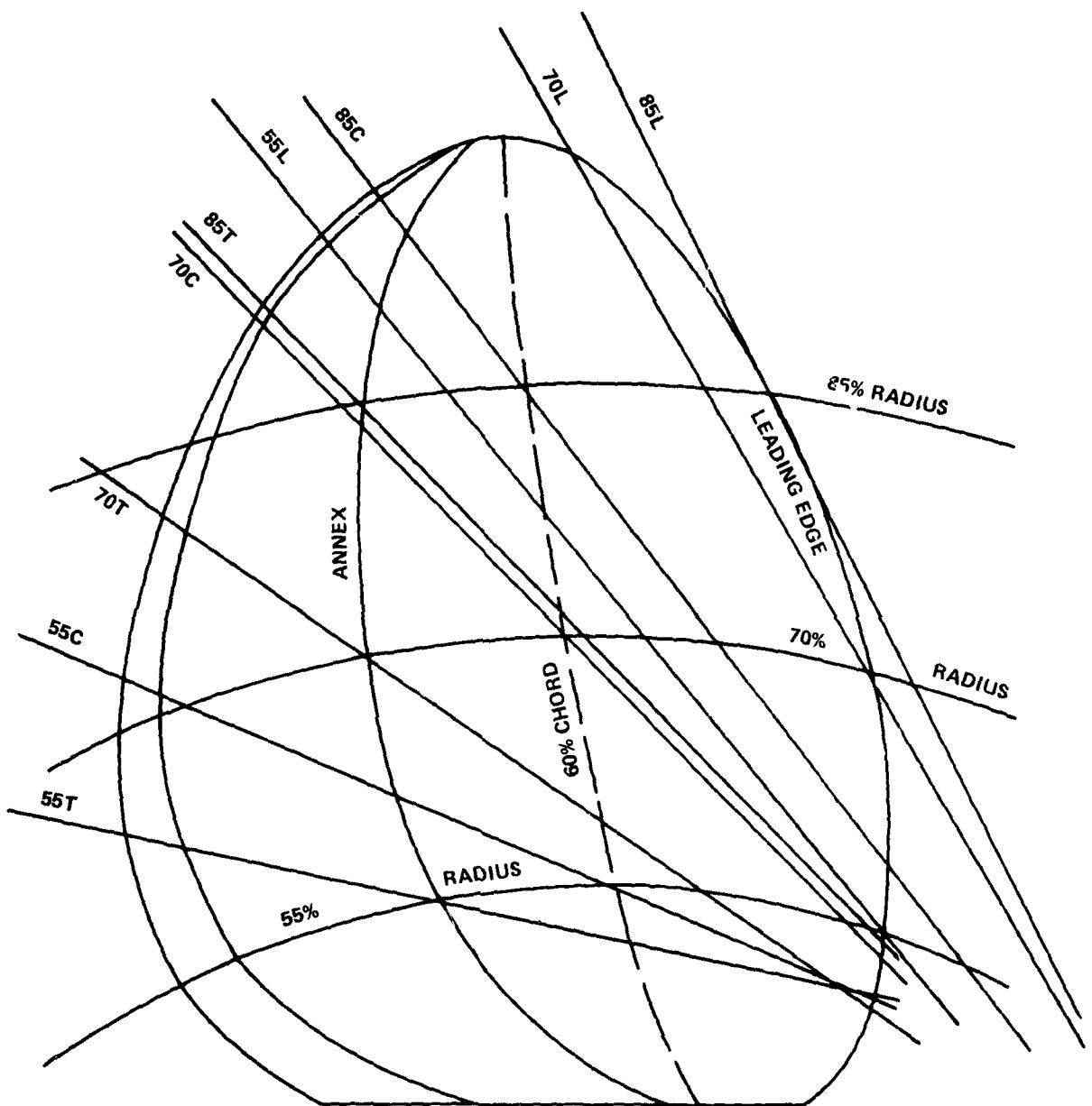
Figure 1 - SES-100B Propeller Blade with Waterlines
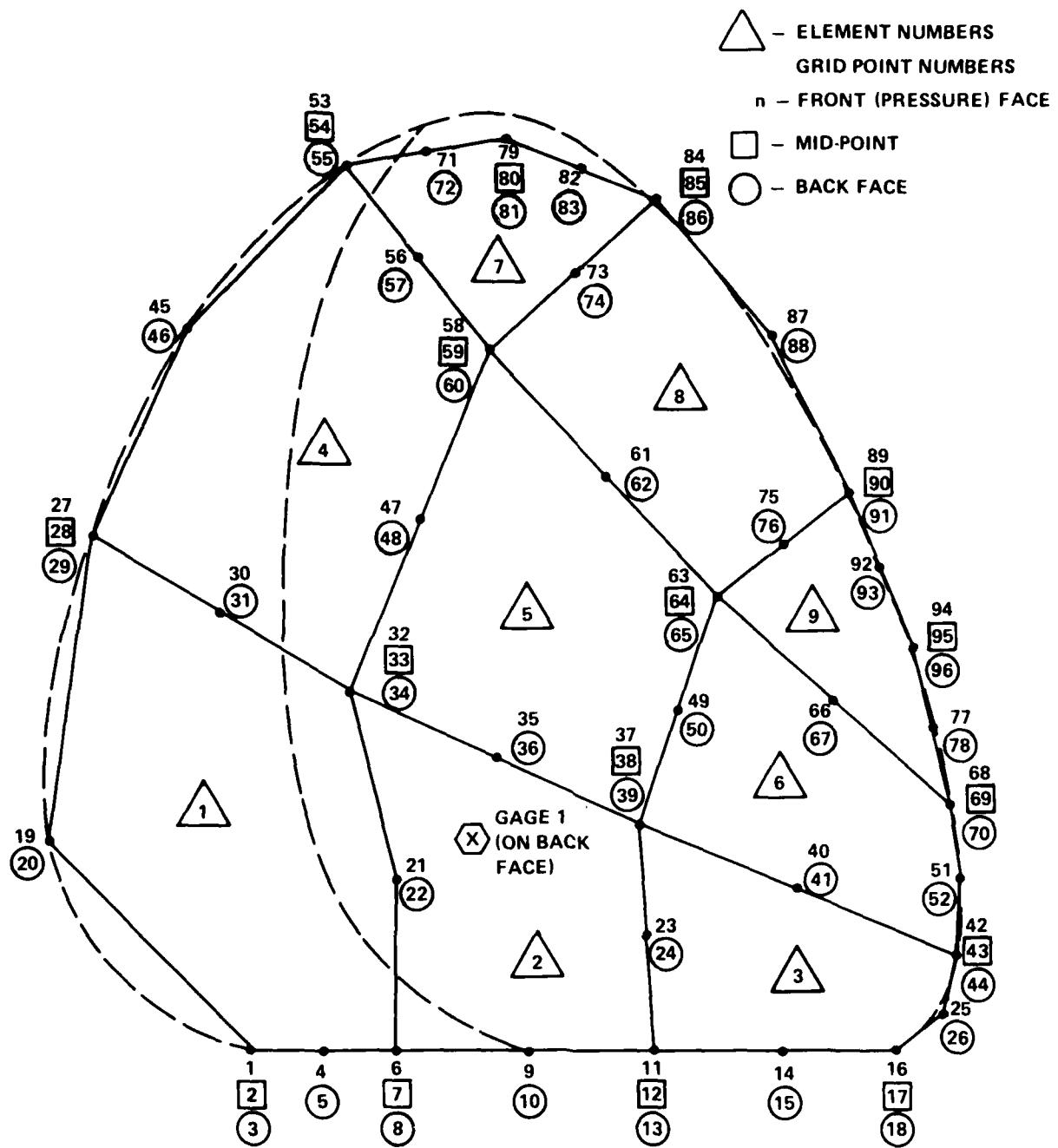
Figure 2 – Representation of Propeller Blade with Finite Elements
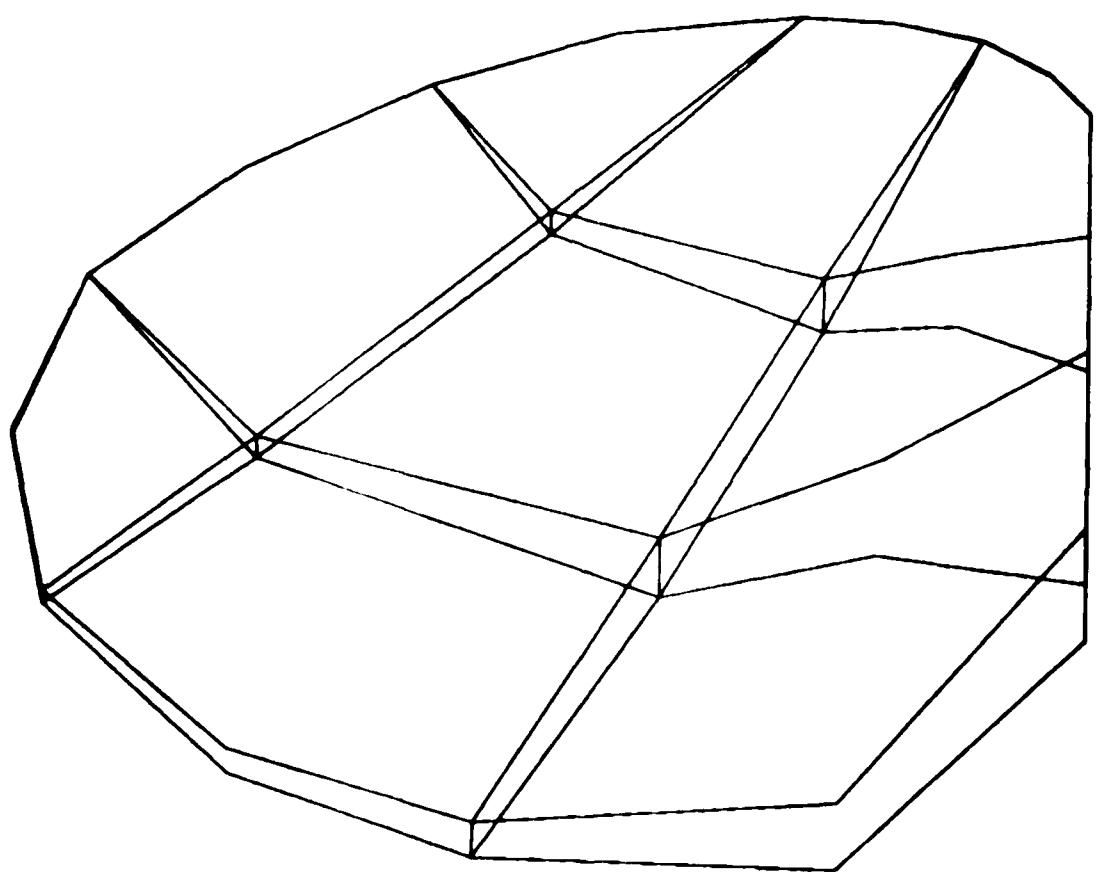
Figure 3 - Finite Element Idealization of Propeller Blade

27
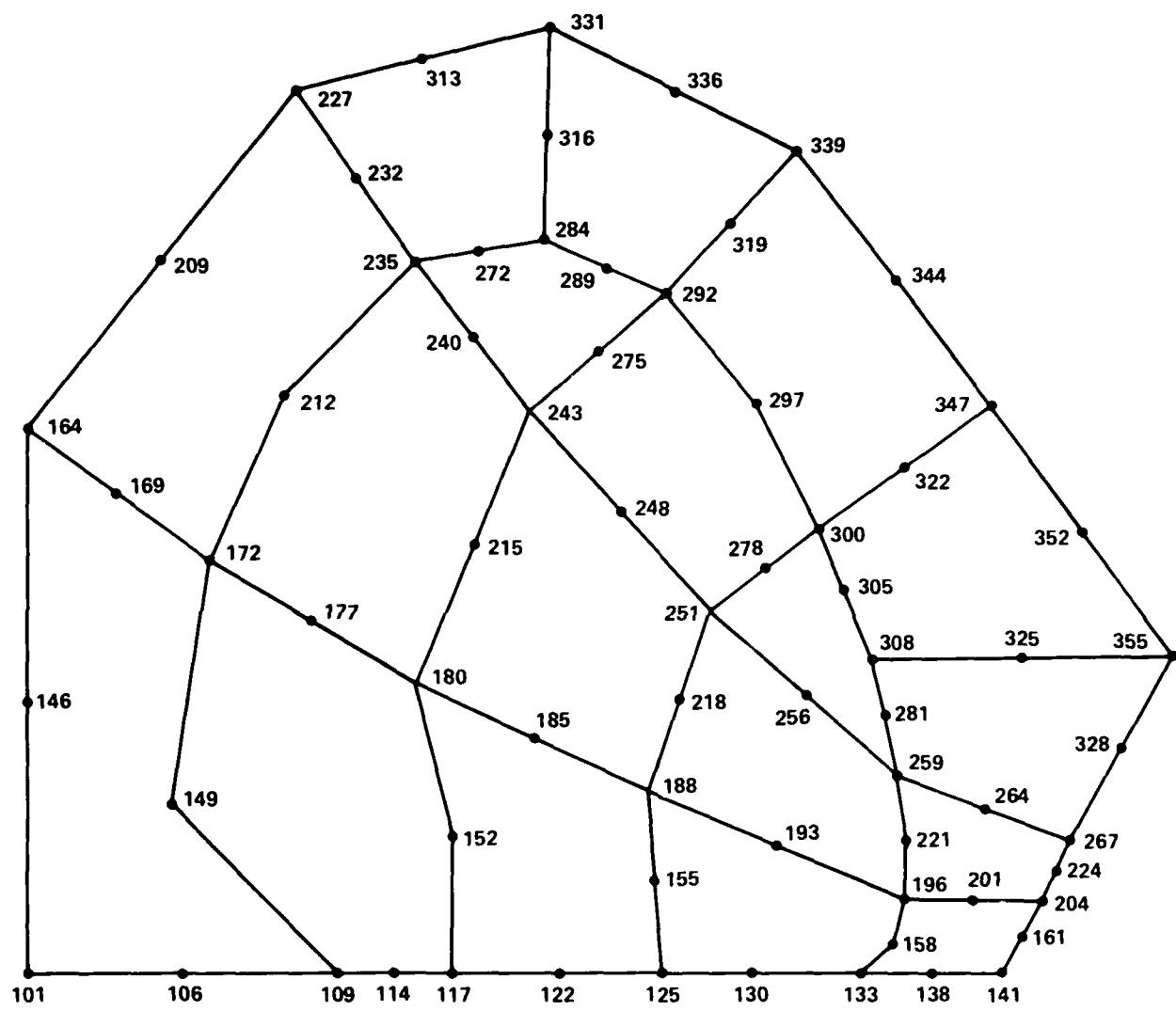
Figure 4 - Representation of Fluid-Structure Contact Face of Water Mass
with Finite Elements
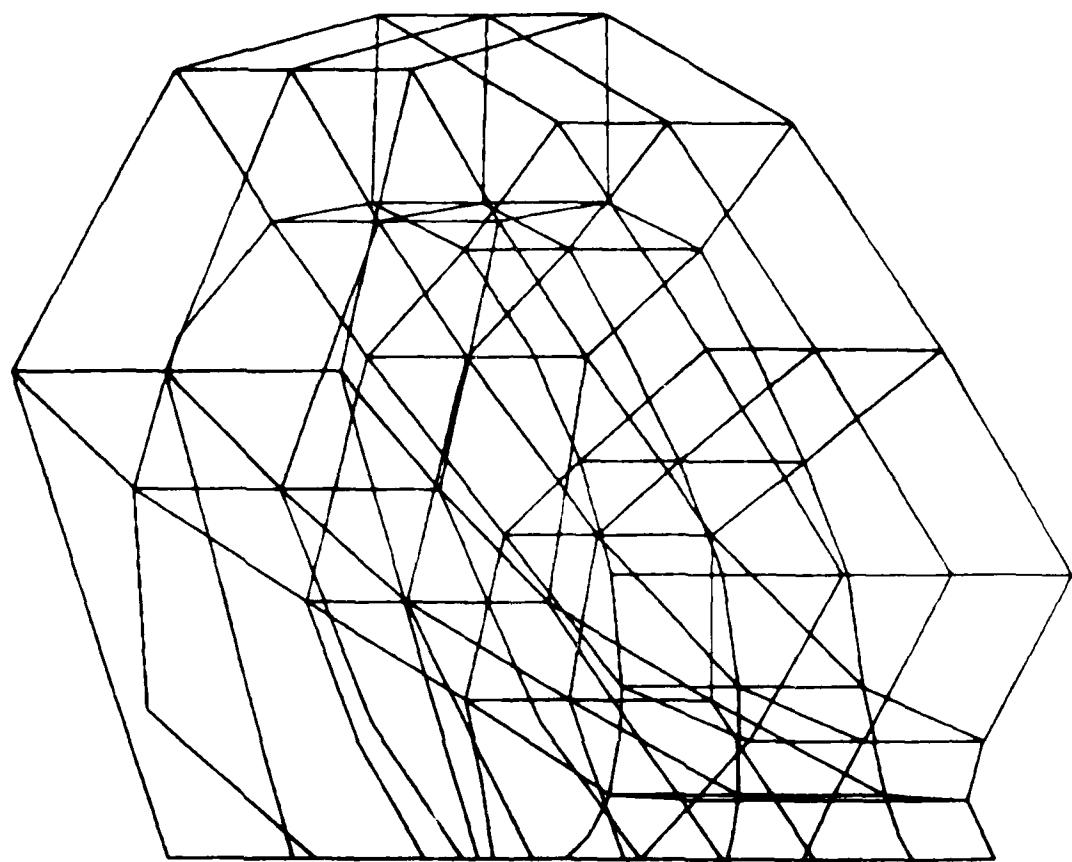
Figure 5 – Finite Element Idealization of Water Mass
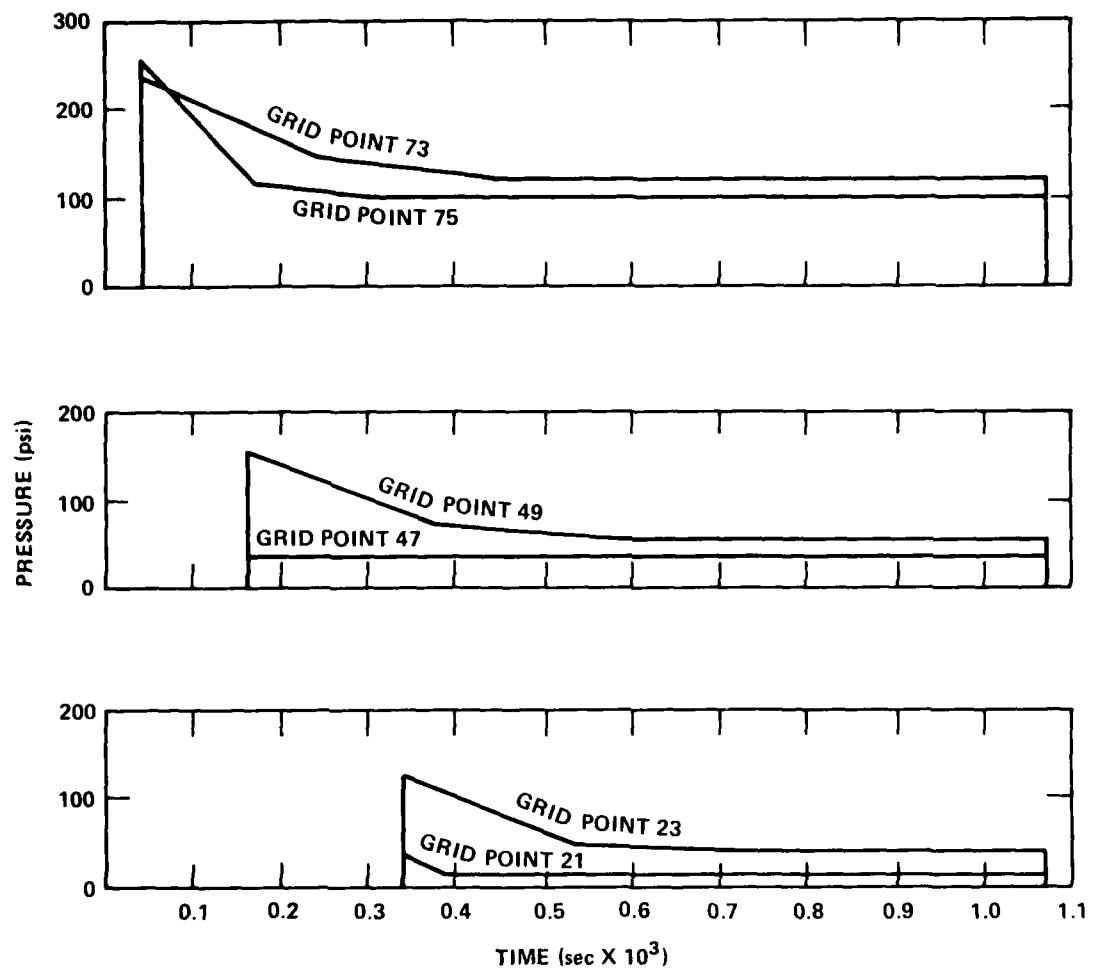
Figure 6 – Time-Dependent Blade Pressures
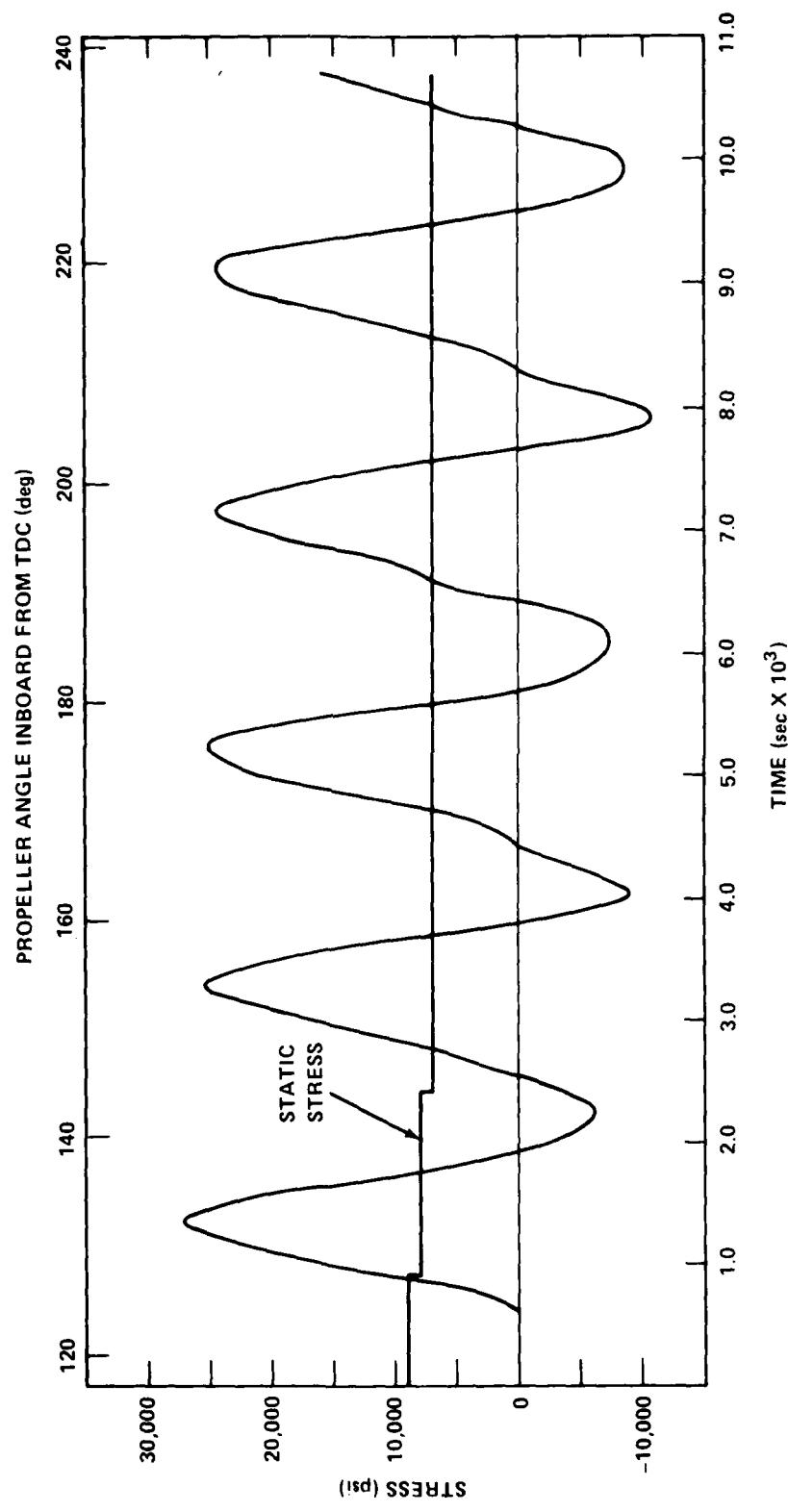
Figure 7 - Calculated Radial Stress in Progressively Submerging Propeller Blade at Grid Point 22
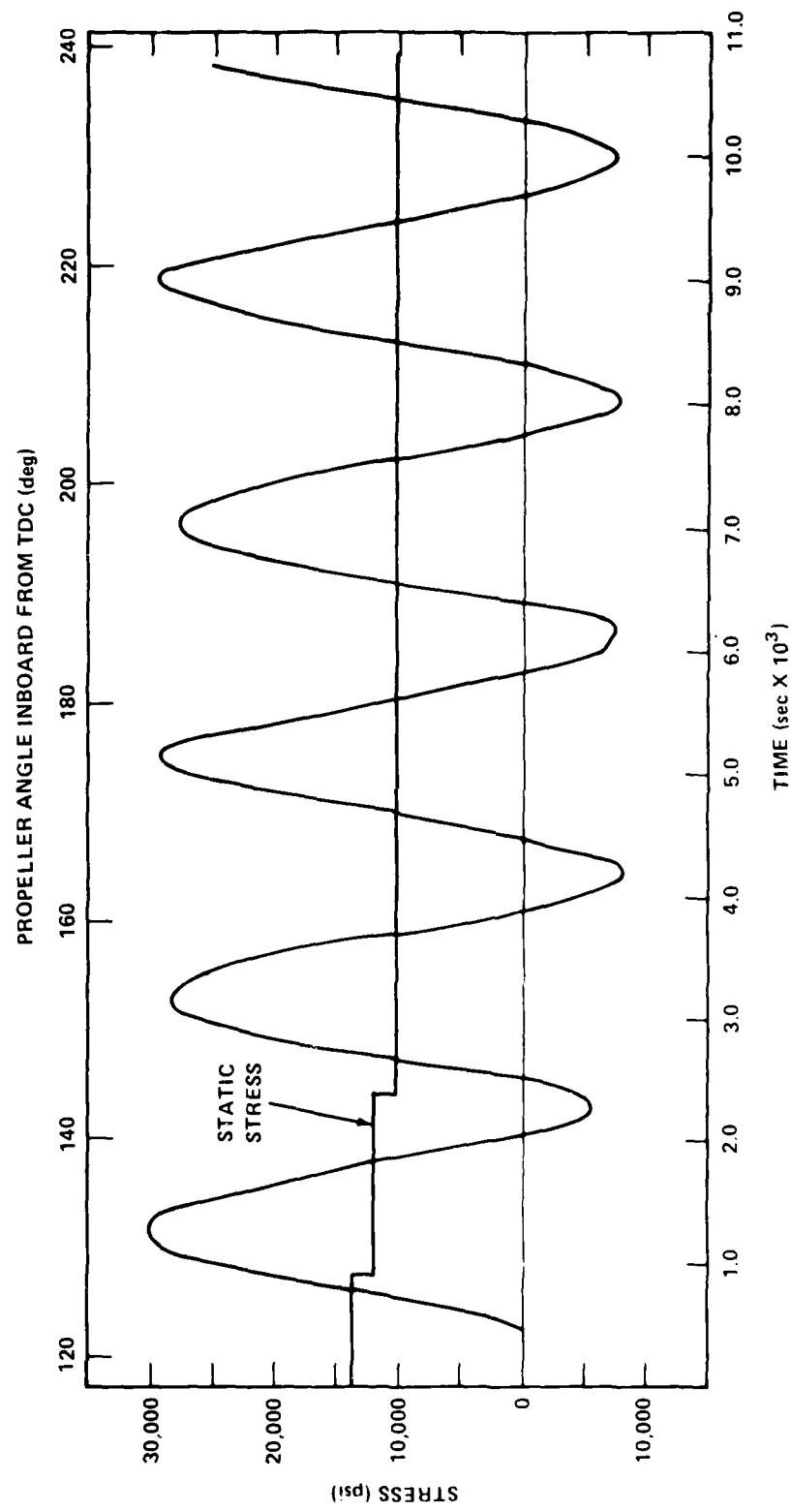
Figure 8 - Calculated Radial Stress in Progressively Submerging Propeller Blade at Grid Point 36
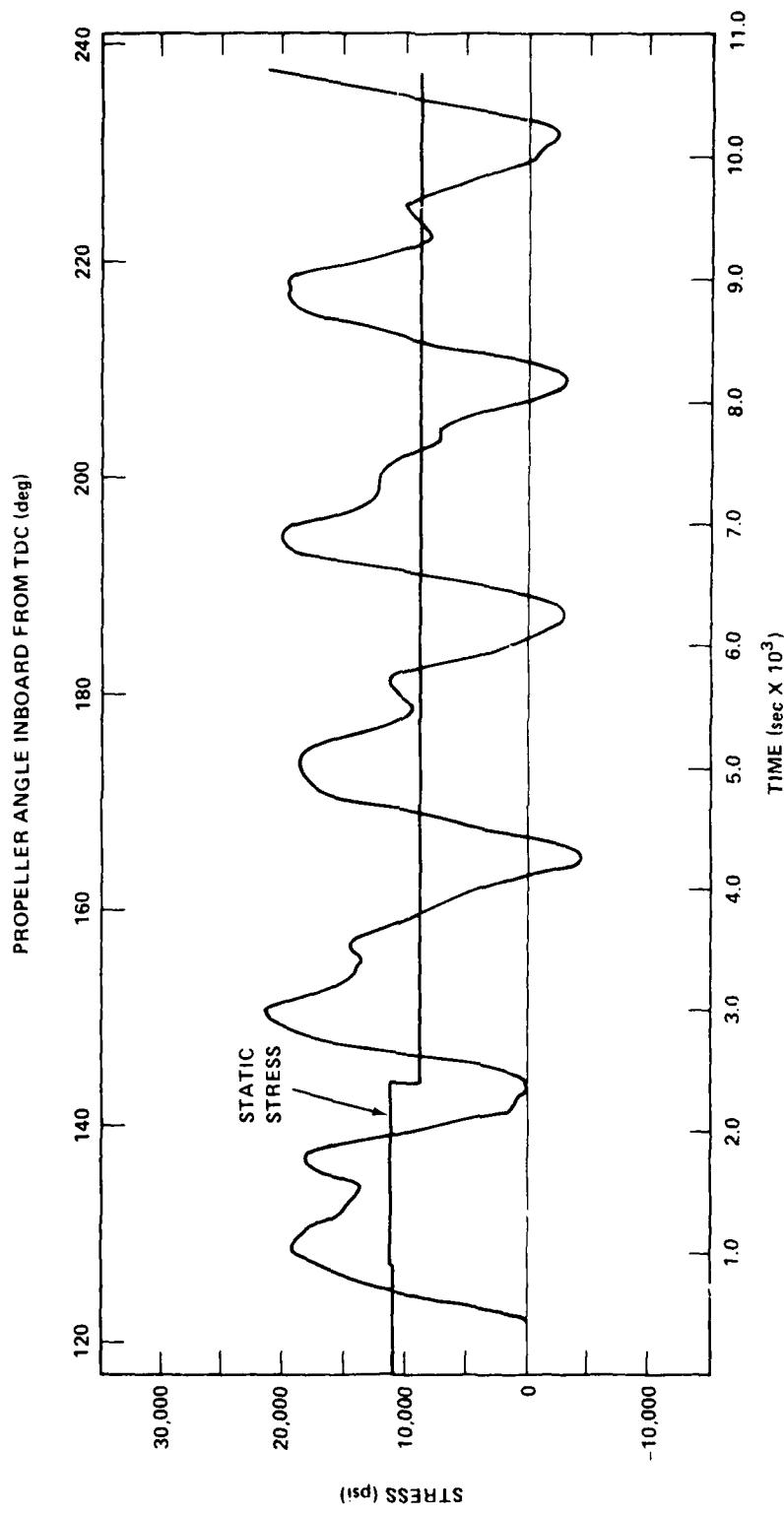
Figure 9 — Calculated Radial Stress in Progressively Submerging Propeller Blade at Grid Point 39

PROPELLER ANGLE INBOARD FROM TDC (deg)
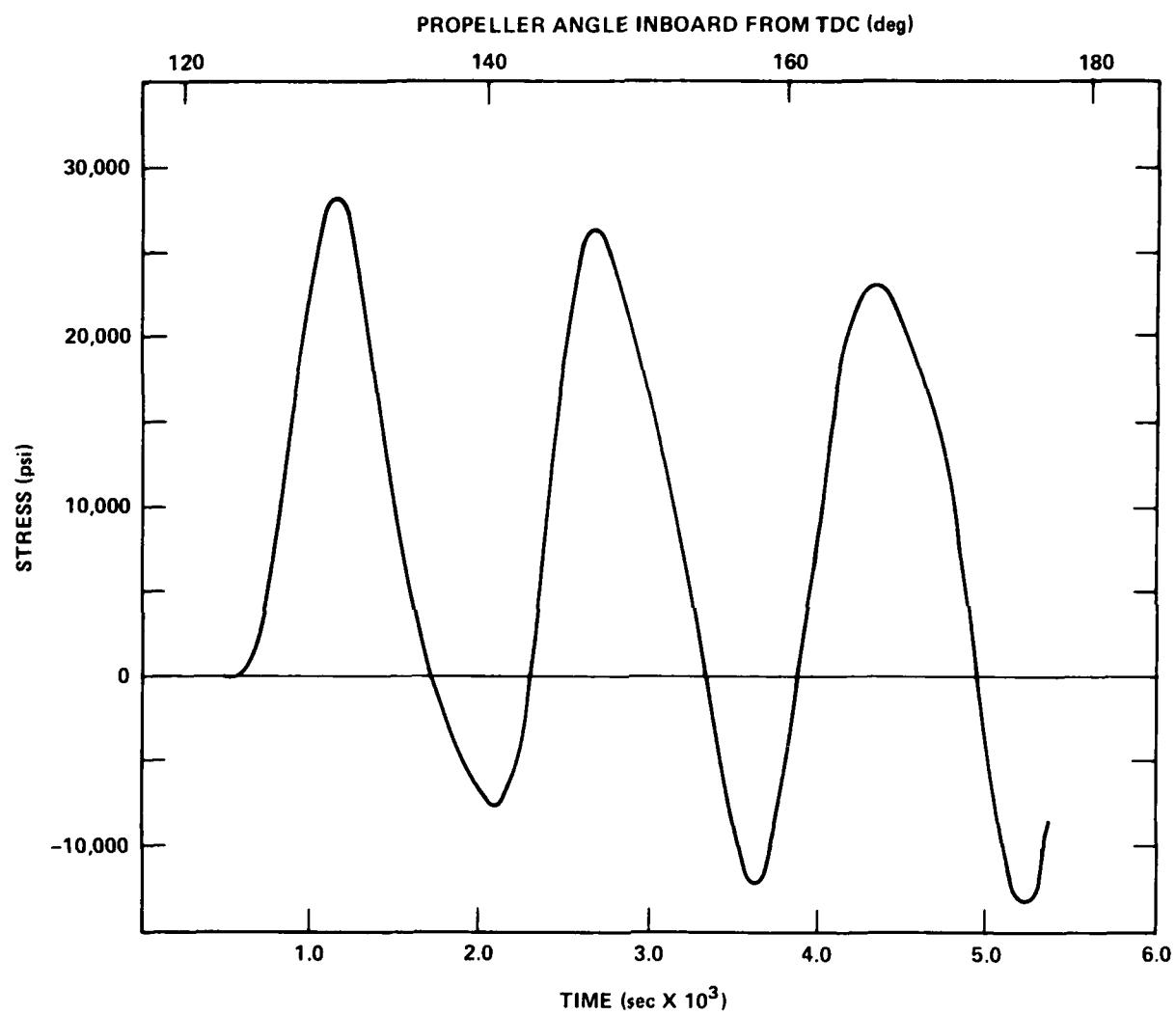
Figure 10 — Calculated Radial Stress at Grid Point 22 of
Propeller Blade in Air with Applied Dynamic Forces

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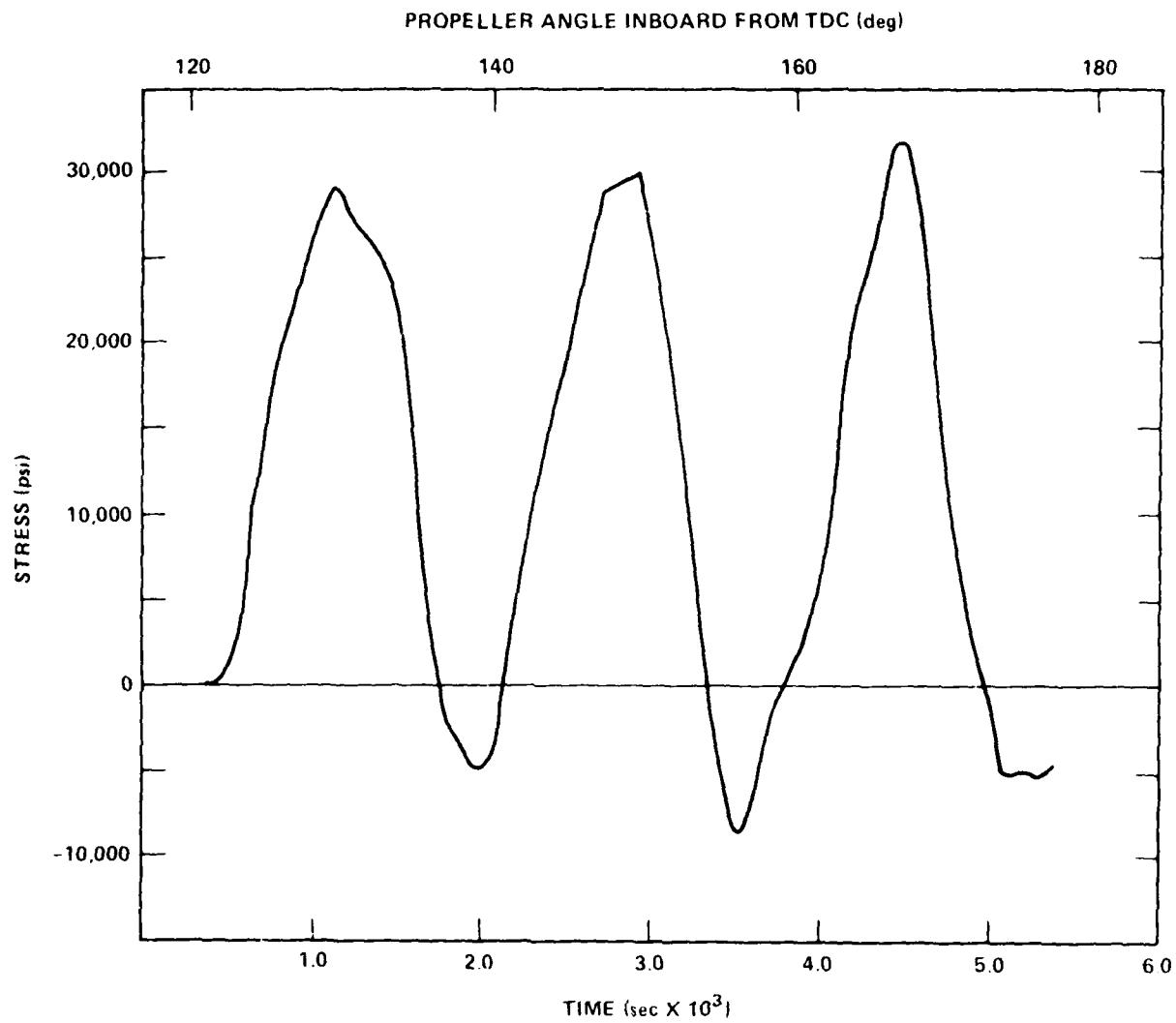
Figure 11 – Calculated Radial Stress at Grid Point 36 of
Propeller Blade in Air with Applied Dynamic Forces
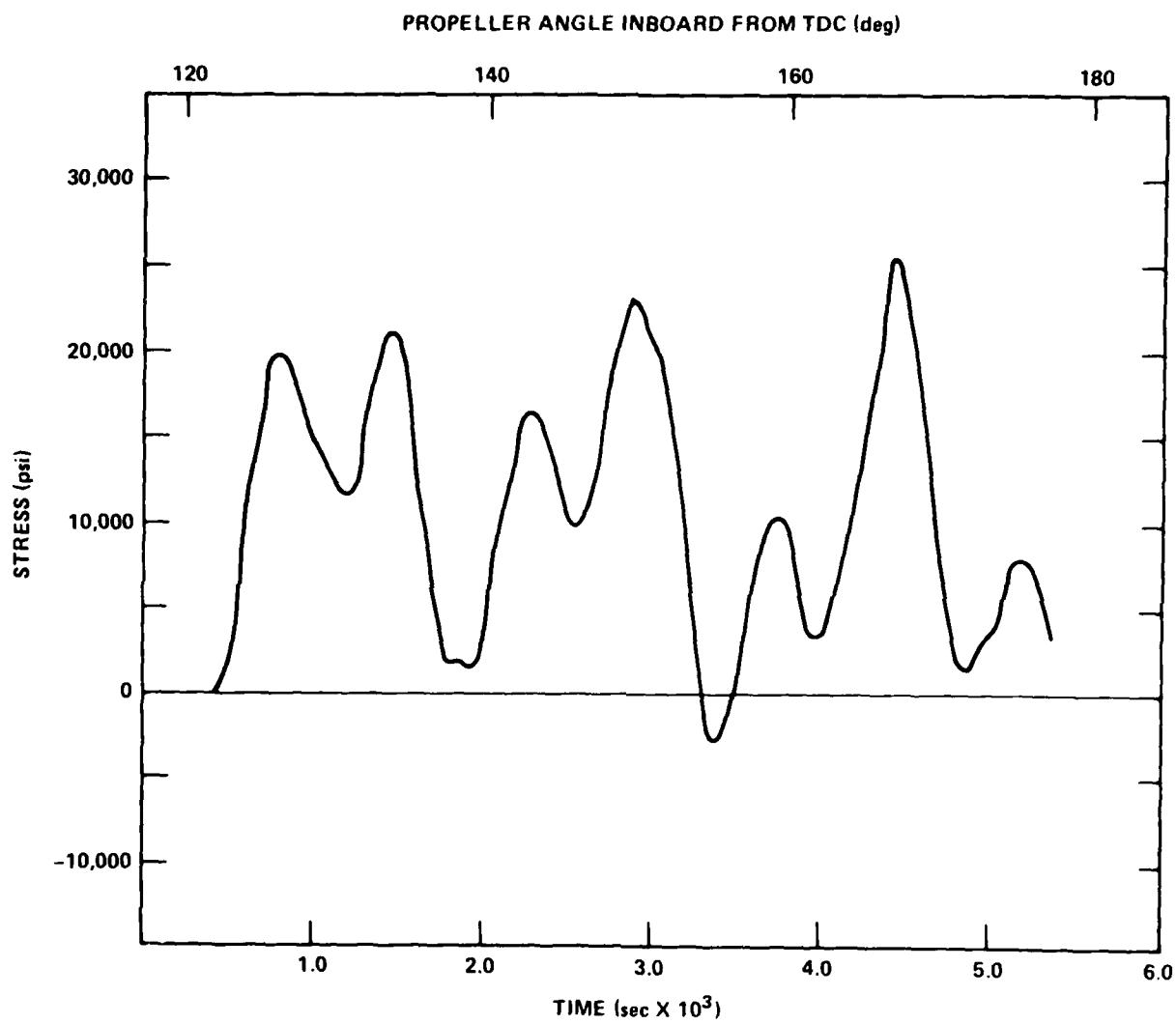
Figure 12 — Calculated Radial Stress at Grid Point 39 of
Propeller Blade in Air with Applied Dynamic Forces
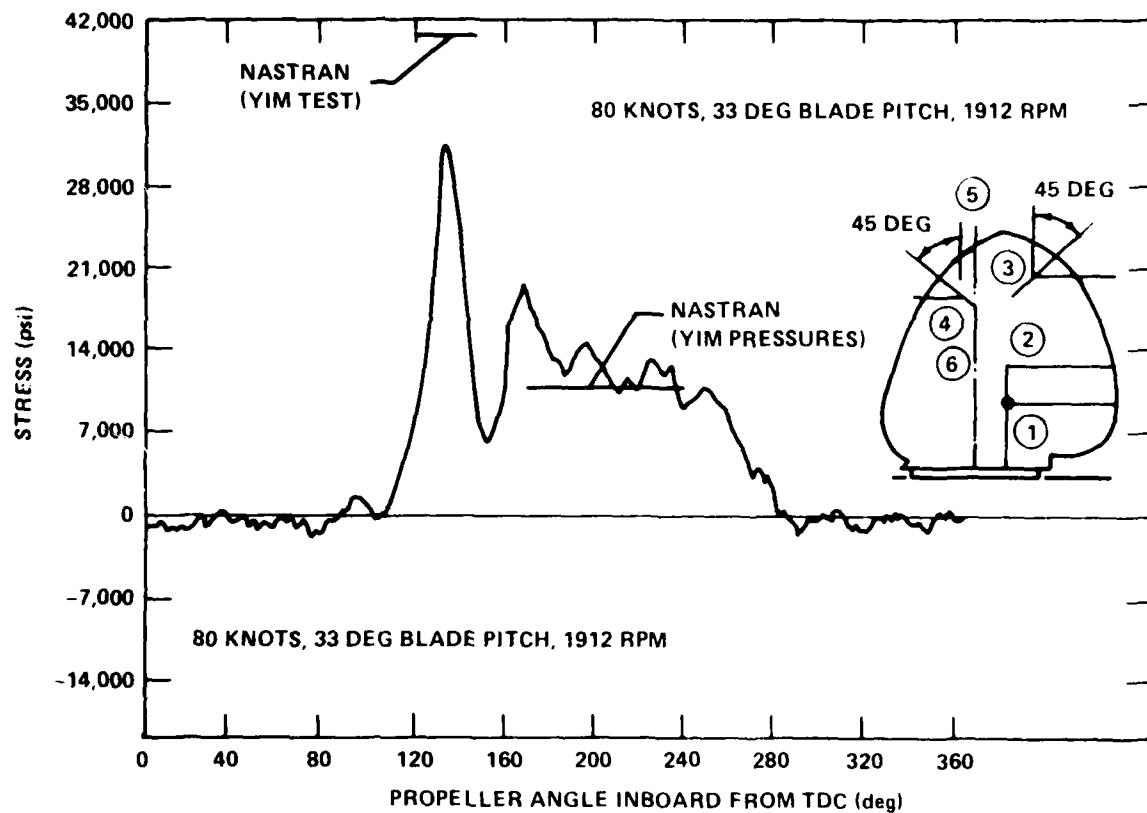
Figure 13 - Experimentally Determined Radial Stress in
SES-100B Propeller Blade at Gage 1

©(From Reference 5)

TABLE 1 - CALCULATED NATURAL FREQUENCIES OF P3604 PROPELLER BLADE

Vibration Mode, N	Calculated Frequencies		Frequency Ratio, $\frac{\text{in Water}}{\text{in Air}}$
	In Air	In Water	
1	461	225	0.49
2	1228	671	0.55
3	168ɔ	774	0.46
4	2397	1171	0.49
5	2613	1315	0.50

TABLE 2 - NATURAL FREQUENCIES OF SES-100B PROPELLER BLADE

Vibration Mode, N	Calculated Frequencies			
	In Air	In Water		
		Stage 1	Stage 2	Stage 3
1	624	524	425	420
2	1399	1037	924	916
3	1679	1316	1206	1158
4	2488	1893	1644	1581
5	2612	2045	1815	1797

APPENDIX - INPUT DATA PREPARATION

Input required for the vibration and transient response analyses in this report will be described using the SES-100B calculations as examples. Inputs described will be those required for the fluid H and L matrix runs, propeller vibration runs in water, and propeller transient response runs, with progressive submergence of the blade. The fluid matrix is the same for either the vibration or the transient response runs.

NASTRAN input decks consist of control cards, an Executive Control deck, a Case Control deck, and a Bulk Data deck. Formats for all cards used here are defined in the NASTRAN User's Manual . The DMAP ALTER instructions contained in the Executive Control Deck and the checkpoint dictionaries apply only to NASTRAN Level 17.

FLUID MATRIX CALCULATION

To obtain a series of fluid H and L matrices, one for each stage of submersion, one static stress computer run is made for each stage. These are basically static stress (Rigid Format 1) runs, utilizing CIHEX2 elements. For convenience, all grid points should be assigned numbers higher than those to be assigned to any grid points of the propeller. The element and grid point data are assembled in the usual way, with the following exceptions and notations.

1. All degrees of freedom of all grid points on the outer boundary, except for those on that part of the fluid-structure interface surface that are to be in contact with the propeller during the current stage, are constrained with SPC cards.

2. All but one translational degree of freedom (components 1, 2, or 3) of all other grid points are constrained.

3. Material properties are input on a MAT1 card. The value of the shear modulus entered is the reciprocal of the mass density of water, $1/\rho$, for the present case in which water contacts only one side of the blade. Young's modulus is a very large factor, say 10^{20}, times the shear modulus. No value is input for Poisson's ratio, so that the NASTRAN program will compute a value.

4. Unit pressure is applied on the element faces of the fluid - structure interface which are to be in contact with the propeller in the present stage. Input is by means of PLOAD3 cards. The unit pressure can be either positive or negative, as the sign will not affect the final result.

5. All grid points in contact with the propeller during this stage are listed on ASET1 cards.

The Executive Control and Case Control decks, and two additional catalog instructions which must be included in the control cards, are shown in Figure A.1. The two instructions identify two permanent files, HMATRIXSTEP1, and LOADSANDTABLES1, which will contain the H matrix and other information, respectively.

For the second and succeeding stages of submersion, the only physical change is that a new set of grid points comes into contact with the propeller blade. This set will generally include all the gridpoints included in the previous stage of submersion. For each succeeding run, then, the grid points newly in contact with the propeller must be added to the set of ASET1 points and removed from the SPC set for which all degrees of freedom are constrained. The element faces newly in contact with the propeller must be added to the set of loaded element faces, and the CATALOG

cards must be changed to assign new names to the H matrix and other data. The names used here for the second step were HMATRIXSTEP2 and LOADSANDTABLES2.

The printout of the "PG" matrix, or list of equivalent forces, is shown in Figure 15. It was necessary to obtain this matrix before constraints were applied in order to obtain all three components for each grid point; consequently, the zeros for all other unloaded components were also printed out. Each group of three non-zero numbers represents the three components of force at a fluid grid point in contact with a propeller grid point. The numbers are given in the order in which the fluid grid points are numbered. These values are to be entered as L^T matrix terms on DMIG cards on which the matching fluid and propeller interface grid points will also be listed. The procedure for entering these terms on DMIG cards is best understood by examining the example to be presented later.

VIBRATION ANALYSIS

The Executive Control and Case Control decks for the vibration analysis of a submerged propeller, and two ATTACH instructions which must be included with the control cards, are given in Figure A.2. The file names on these two cards identify the H matrix and other data which have been created by a previous run. In this example, the names identify the third, or fully-submerged, case. The ALTER routine in the Executive control deck contains two partition (PARTN) instructions, one of which contains the matrix name, PVEC3. That name was arbitrarily chosen to identify a partitioning column matrix of the same name to be input in the bulk data.

The bulk data is set up basically as a propeller vibration run, with the following additions:

1. All fluid points in contact with the propeller (in this fully-submerged case, all fluid-structure interface points) are listed as scalar points on SPOINT cards in this propeller run.

2. Constraints on the zero component of these scalar points are input on SPC cards.

3. Two column matrices, PVECD1 and PVEC3, are input. In this example the total number of unconstrained degrees of freedom is 96x6, or 576 for the propeller, plus 40 for the scalar points, or 616. Dimensions of the two column matrices, therefore, are 1x616. All entries in PVECD1 are zero, and all except the last 40 (assuming the SPOINT numbers are higher than all propeller grid point numbers) of the PVEC3 entries are zero. The remaining 40 entries are 1.0.

4. The L^T matrix terms are input on DMIG cards. In this case, 40x3 terms are input.

TRANSIENT RESPONSE ANALYSIS

The procedures for preparing the additional bulk data input for the vibration analysis are essentially the same as those for the transient response case, which will be illustrated in more detail.

The Executive Control, Case Control, and Bulk Data decks, and the four additional control cards, for the first stage of submersion of the transient response case are shown in Figure A.4. Of the four control cards, the two ATTACH instructions retrieve the appropriate H matrix for this step, as in the vibration calculation. The REQUEST and CATALOG instructions effect the storage of the checkpoint file named SUBSTP1, required for the restart. The bulk data input consists of the same data as for a straight-forward transient response analysis, and additional SPOINT, SPC, DMIG, and

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DMI data similar to that for the vibration in water case. The following comments apply to the additional data;

1. All fluid grid points to come into contact with the propeller during the course of the analysis (not just those in contact in the current stage of submersion) must be listed as scalar points on SPOINT cards, and also on SPC cards because scalar points cannot be added after solution of the problem has begun.

2. PVECD1 and PVEC1 matrices have the same dimensions for all stages, in this example 1x 616. The number of "1.0" terms in PVEC1, however, in this case 18, must be equal to the number of fluid points in contact with the propeller for the current stage, and the placement of these terms within the "scalar point section" of the PVEC1 column (the last 40 numbers) must correspond to the positions of the 18 contact points within the "scalar point section." All degrees of freedom of propeller grid points and scalar points are represented in the PVEC1 column in numerical order. In this example the fluid points were numbered so that the portions of the blade with the highest numbered points contact the water first; thus any "1.0" entries in PVEC1, or PVEC2, etc., are the last terms in the column.

3. The L^T matrix input by DMIG cards for this stage was made up from the corresponding "PG" matrix printout from the first stage fluid run, given in Figure A.2. The current run is terminated when the time covered by the TSTEP card, that is, number of steps times length of each step (in this case 0.9095×10^{-3} seconds), has elapsed.

To continue the analysis for the second stage of submersion, a restart run is carried out, with the following changes to the deck:

1. The two ATTACH instructions and the CATALOG instruction described

for the first run are replaced with the following control cards:

    ATTACH,OPTP,SUBSTP1,ID=CSRV.

    ATTACH,INPT,HMATRIXSTEP2,ID=CSRV.

    ATTACH,UT1, LOADSANDTABLES2,ID=CSRV.

    CATALOG,NPTP,SUBSTP2,ID=CSRV.

2. The checkpoint dictionary produced by the previous run is added to

the Executive Control deck. Also, PVEC1, which appears in one of the

PARTN instructions, is changed to PVEC2. The following lines are added

to the previous ALTER routine and left for the remaining restart runs:

    ALTER   143,143

    CHKPNT   K2PP, K2DD,M2DD,B2DD,MDD,KDD $

    ALTER   159,159

3. The TSTEP card, TSTEP=21, in the Case Control deck, is replaced with

TSTEP=22.

4. The Bulk Data deck consists of the following cards:

    a. A delete (/) card which eliminates the previous DMIG cards.

    b. DMIG cards, which represent the L^T matrix for stage two.

    c. DMI cards for a new column matrix, PVEC2. Dimensions are the

        same as for PVEC1, but the number of "1.0" terms is changed to

        represent the new set of points in contact with the propeller.

        In this case, the last 28 terms are now 1.0.

    d. A new TSTEP Bulk Data card, identified as TSTEP number 22,

        to correspond to the Case Control TSTEP card. This card

        should contain the correct number of time steps so that the

        total time defined will just cover the current stage of

submersion. In this second stage, 28 steps were used.

To continue with the third and any succeeding steps, the procedures for the second stage are followed. The REQUEST and CATALOG control cards and the CHKPNT Executive Control deck card are not required in the final run.

```
CATALOG,INPT,HMATRIXSTEP1,ID=CSRV.
CATALOG,UT1,LOADSANDTABLES1,ID=CSRV.



            N A S T R A N    E X E C U T I V E    C O N T R O L    D E C K



ID SES PROPELLER FLUID IDEALIZATION
APP DISPLACEMENT
SOL 1,0
DIAG 1,8,14,22
TIME 60
ALTER    97
MATPRN   KAA,,,,//$
OUTPUT1  ,,,,//C,N,-1 $
OUTPUT1  KAA,,,,// $
JUMP     LBL7 $
ALTER    112
MATPRN   PG,ASET,,,// $
OUTPUT2  PG,EQEXIN,ASET,,//C,N,0/C,N,11$
TABPT    EQEXIN,,,,// $
JUMP     MEL $
ALTER    141
LABEL    MEL  $
EQUIV    PG,PGG $
ALTER    143
JUMP     LBLOFP $
ALTER    165
JUMP     FINIS $
ENDALTER
CEND



            C A S E    C O N T R O L    D E C K


TITLE = SES PROPELLER FLUID
SUBTITLE = ADDED MASS TERMS
SPC = 11
LOAD = 1
DISPLACEMENT = ALL
MAXLINES = 500000
BEGIN BULK
```

Figure A.1 - Fluid Run Partial Input

SES PROPELLER FLUID
ADDED MASS TERMS

MATRIX PG   (GINO NAME 101) IS A REAL   1 COLUMN X   1554 ROW RECTANG MATRIX.

ROWS   805 THRU   1245

THE NUMBER OF NON-ZERO WORDS IN THE LONGEST RECORD =   54

THE DENSITY OF THIS MATRIX IS   3.47 PERCENT.

Figure A.2 - Matrix PG of Equivalent Nodal Forces

```
ATTACH,INPT,HMATRIXSTEP3,ID=CSRV.
ATTACH,UT1,LOADSANDTABLFS3,ID=CSRV.



            N A S T R A N     E X E C U T I V E     C O N T R O L     D E C K


ID VIBRATION SES PROP IN WATER
APP DISPLACEMENT
SOL 3,C
DIAG 1,4,14,22
TIME 6C
ALTER   53
DPD     DYNAMICS,GPL,SIL,USET/GPLD,SILD,USETD,,,,,,,EED,EQDYN/V,N,
        LUSET/V,N,LUSETD/V,N,NOTFL/V,N,NODLT/V,N,NOPSDL/V,N,NOFRL/V,
        N,NONLFT/V,N,NOTRL/V,N,NOEED/C,N,/V,N,NOUE $
SAVE    NOEED,LUSETD $
MTRXIN  CASECC,MATPOOL,EQDYN,,/K2DPP,M2DPP,B2PP/V,N,LUSETD/V,
        N,NOK2DPP/V,N,NOM2DPP/V,N,NOB2PP $
PARTN   K2DPP,,PVEC3/UNUSED,ATMAT,,/C,N,1 $
INPUTT1 /,,,,,/C,N,-1 $
INPUTT1 /HMAT,,,,,/ $
SOLVE   HMAT,ATMAT/HIAT/C,N,1 $
MPYAD   ATMAT,HIAT,MGG/MGGTEM/C,N,1 $
PARTN   MGGTEM,PVECD1,/MGGNEW,,,,/C,N,-1/C,N,2/C,N,6 $
PARAM   //C,N,MPY/V,N,PDUM/C,N,1/C,N,-1 $
EQUIV   MGGNEW,MGG/PDUM $
JUMP    DICK $
MATPRN  MGGNEW,MGG,,,,// $
LABEL   DICK $
ALTER   9F,97
ENDALTER
CHKPNT  YES
CEND



            C A S E     C O N T R O L     D E C K


TITLE=SES PROP VIBRATION
SUBTITLE = PARTIALLY SUBMERGED PROPELLER
LABEL = INVERSE POWER METHOD
ECHO = BOTH
K2PP = STFF
METHOD=41
SPC=1C
DISPLACEMENT = ALL
MAXLINES = 5J0DCJ
BEGIN BULK
```

Figure A.3 – Propeller Vibration Run Partial Input

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Figure A.4 - Propeller Transient Response Run Input for Stage 1

```
REQUEST,NPTP,*PF.
ATTACH,INPT,HMATRIXSTEP1,ID=CSRV.
ATTACH,UT1,LOADSANDTABLFS1,ID=CSRV.
CATALOG,NPTP,SUBSTP1,ID=CSRV.
```

N A S T R A N   E X E C U T I V E   C O N T R O L   D E C K   E C H O

```
TO TRANSIENT RESPONSE OF SES PROPELLER IN WATER
APP DISPLACEMENT
SOL 9,0
DIAG 1,8,14,22
TIME 60
ALTER    72
DPD      DYNAMICS,GPL,STL,USET/GPLD,SILD,USETD,TFPOOL,DLT,,,NLFT,TRL,,
         EQDYN/V,N,LUSET//V,N,LUSETD/V,N,NOTFL/V,N,NODLT/V,N,NOPSDL/V,
         N,NOFRL/V,N,NONLFT/V,N,NOTRL/V,N,NOEED/C,N,/V,N,NOUE $
SAVE     LUSETD,NODLT,NONLFT,NOTRL,NOUE $
MTRYIN   CASECC,MATPOOL,EQDYN,,TFPOOL/K2DPP,M2DPP,B2PP/V,N,LUSETD/V,N,
         NOK2DPP/V,N,NOM2DPP/V,N,NOB2PP $
SAVE     NOK2DPP,NOM2DPP,NOB2PP $
PARTN    K2DPP,,PVEC1/UNUSED,ATMAT,,/C,N,1 $
INPUTT1  7,,,,,/C,N,-1 $
INPUTT1  /HMAT,,,,,/ $
SOLVE    HMAT,ATMAT/HIAT/C,N,1 $
MPYAD    ATMAT,HIAT,MGG/MGGTEM/C,N,1 $
PARTN    MGGTEM,PVEC1,/MGGNEW,,,,/C,N,-1/C,N,2/C,N,6 $
EQUIV    MGGNEW,MGG $
JUMF     DICK $
MATPRN   MGGNEW,MGG,,,// $
LABEL    DICK $
ALTER    114,115
ALTER    128,129
ENDALTER
CHKPNT   YES
CEND
```

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Figure A.4 (Continued)

SES PROPELLER DYNAMIC RESPONSE
PARTIALLY SUBMERGED PROPELLER

DIRECT TRANSIENT RESPONSE

C A S E   C O N T R O L   D E C K   E C H O

```
CARD
COUNT
   1     TITLE = SES PROPELLER DYNAMIC RESPONSE
   2     SUBTITLE = PARTIALLY SUBMERGED PROPELLER
   3     LABEL = DIRECT TRANSIENT RESPONSE
   4     ECHO = BOTH
   5     DLOAD = 10
   6     TSTEP = 21
   7     K2PP = STFF
   8     SET 5 = 2
   9     ELSTRESS = 5
  10     SPC = 10
  11     DISPLACEMENT=ALL
  12     MAXLINES = 500000
  13     BEGIN BULK
```

Figure A.4 (Continued)

S O R T E D   B U L K   D A T A   E C H O

CARD COUNT		1	2	3	4	5	6	7	8	9	10
1-		CIHEX2	1	38	6	22	8	19	3	32	3	+11
2-		+11	34	4	21	28	20	30	33	2	+21
3-		+21	2	31	29	12	27	10	8	7	+12
4-		CIHEX2	6	30	11	24	13	21	37	38	+22
5-		+12	30	9	23	73	22	35			
6-		+22		76	34		32		13	12	+13
7-		CIHEX2		36	16	17	18	15	42	43	+23
8-		+13	11	14	25	26	24	23			
9-		+23	44	41	39	34	27	40	29	28	+14
10-		CIHEX2	4	70	32	73	34	31	58	59	+24
11-		+14	27	70	47	48	46	45			
12-		+24	40	57	55	54	53	56	34	33	+15
13-		CIHEX2	5	30	77	38	59	76	63	64	+25
14-		+15	32	35	49	50	48	47			
15-		+25	66	62	60	59	58	61	39	38	+16
16-		CIHEX2	6	70	42	43	44	41	68	69	+26
17-		+16	77	40	51	52	50	49			
18-		+26	70	67	65	64	63	66	55	54	+17
19-		CIHEX2	7	56	58	59	60	57	84	85	+27
20-		+17	53	87	73	74	72	71			
21-		+27	86	30	81	88	79	82	60	59	+18
22-		CIHEX2	8	30	63	64	65	62	89	90	+28
23-		+18	58	61	75	76	74	73			
24-		+28	91	78	86	85	84	87	65	64	+19
25-		CIHEX2	9	78	68	69	70	67	94	95	+29
26-		+19	63	66	77	78	76	75			
27-		+29	96	93	91	90	89	92			
28-		CAREA	121	21	1	6.20	21	2	1.17		
29-		CAREA	121	21	5	6.68					
30-		OADER	123	23	3	10.74	23	2	-0.82		
31-		CAREA	123	73	1	9.40					
32-		CAREA	147	47	1	9.32	47	2	1.07		
33-		CAREA	147	47	3	14.91					
34-		CAREA	149	49	1	11.79	49	2	-0.91		
35-		CAREA	149	49	3	13.97					
36-		CAREA	173	73	1	5.57	73	2	.0		
37-		CAREA	173	73	3	9.77					
38-		CAREA	175	75	1	6.73	75	2	-0.75		
39-		CAREA	175	75	1	8.53					
40-		DLOAD	10	1.0	1.0	20	1.0	30	1.0	40	+DL1
41-		+DL1	50	1.0	1.0	60	1.0	70	616	1	
42-		CMT	PVECM1	6	2	1	1				
43-		CMT	PVECM1	6	1	.0					
44-		CMT	PVEC1	1	2	1	1		616	1	+PV11
45-		PVEC1	1	599	1.0	1.0	1.0	1.0	1.0	+PV12
46-		+PV11	1.0	1.0	1.0	1.0	1.0	1.0			
47-		+PV12	1.0	1.0	1.0	1.0	1.0	1.0			
48-		CMTG	STFF	0	1	1	1	1	.2148		
49-		CMTG	STFF	53	2	1.0	235	616	.0374		
50-		CMTG	STFF	59	2	1.0	235				

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Figure A.4 (Continued)

SFS PROPELLER DYNAMIC RESPONSE
PORT-TAIL SUBMERGED PROPELLER

DIRECT TRANSIENT RESPONSE

SORTED BULK DATA ECHO

CARD COUNT	. 1	.. 2	.. 3	.. 4	.. 5	.. 6	.. 7	.. 8	.. 9	.. 10
51-	PMIG	STFF	53		235			.3980		
52-	PMIG	CTFF	56	1	240			-.9293		
53-	DMIG	CTFF	56	2	260			-.1753		
54-	PMIG	CTFF	56	3	240			-1.7650		
55-	DMIG	STFF	58	1	243			.6694		
56-	DMIG	STFF	58	2	243			.0311		
57-	PMIG	STFF	58	3	243			1.1226		
58-	PMIG	STFF	61	1	248			-2.8E18		
59-	PMIG	STFF	61	2	248			-.0196		
60-	PMIG	STFF	61	3	248			-3.2924		
61-	DMIG	STFF	63	1	251			.6957		
62-	PMIG	STFF	63	2	251			-.0556		
63-	PMIG	STFF	63	3	251			1.0993		
64-	PMIG	STFF	66	1	256			-1.0471		
65-	DMIG	STFF	66	2	256			.2347		
66-	PMIG	CTFF	66	3	256			-1.4007		
67-	PMIG	CTFF	68	1	250			.2255		
68-	PMIG	CTFF	68	2	259			-.0396		
69-	DMIG	CTFF	68	3	259			.3034		
70-	PMIG	STFF	71	1	272			-.7647		
71-	DMIG	CTFF	71	2	272			-.1286		
72-	DMIG	CTFF	71	3	272			-1.4E90		
73-	PMIG	STFF	73	1	275			-3.0814		
74-	DMIG	CTFF	73	2	275			-.2290		
75-	PMIG	STFF	75	3	275			-5.2498		
76-	DMIG	CTFF	75	1	278			-3.0370		
77-	PMIG	STFF	75	2	278			.2113		
78-	DMIG	CTFF	77	3	278			-4.5228		
79-	DMIG	CTFF	77	2	281			-.7559		
80-	PMIG	CTFF	77	3	281			.1985		
81-	PMIG	STFF	79	1	281			-1.0748		
82-	DMIG	CTFF	79	2	284			.2539		
83-	PMIG	CTFF	79	3	284			.0495		
84-	PMIG	CTFF	80	1	284			.4781		
85-	DMIG	STFF	82	2	289			-.7728		
86-	PMIG	STFF	82	3	289			-.1271		
87-	PMIG	CTFF	82	1	289			-1.6481		
88-	PMIG	STFF	84	2	292			.7079		
89-	PMIG	CTFF	84	3	292			.0276		
90-	DMIG	CTFF	86	1	297			1.1759		
91-	DMIG	CTFF	87	2	297			-2.0082		
92-	PMIG	CTFF	87	3	297			-.0181		
93-	PMIG	CTFF	89	1	300			-3.3411		
94-	PMIG	STFF	89	2	300			.7543		
95-	PMIG	STFF	89	3	300			-.0365		
96-	PMIG	CTFF	92	1	305			1.1260		
97-	PMIG	CTFF	92	2	305			-0.7252		
98-	PMIG	CTFF	92	3	305			.1586		
99-	PMIG	STFF	94	2	305			-1.0591		
100-	PMIG	CTFF	94	1	308			.2940		

SEC PROPELLER DYNAMIC RESPONSE
PARTIALLY SUBMERGED PROPELLER

DIRECT TRANSIENT RESPONSE

S O R T E D   B U L K   D A T A   E C H O

CARD COUNT	.. 1	.. 2	.. 3	.. 4	.. 5	.. 6	.. 7	.. 8	.. 9	.. 10
101-	OMIG	STFF								
102-	OMIG	STFF								
103-	FRDSET		94	94						
104-	GPID	1		-1.99	.8	308		-.0603		
105-	GPID	2		-2.615	.0	308		.3891		
106-	GRID	3		-3.24	.0	2.34		456		
107-	GPID	4		-0.9968	.0	3.5606				
108-	GPID	5		-2.922	.8	1.9315				
109-	GPID	6		-0.0035	.0	7.5311				
110-	GRID	7		-1.3037	.0	2.627				
111-	GRID	8		-2.6039	.0	1.5229				
112-	GPID	9		.9	.0	1.5729				
113-	GPID	10		-1.4559	.0	.0369				
114-	GRID	11		1.276	.0	-0.0426				
115-	GRID	12		.5296	.0	-0.7084				
116-	GPID	13		-0.2169	.0	-1.3742				
117-	GPID	14		1.8833	.0	-1.4086				
118-	GRID	15		.8346	.8	-2.2291				
119-	GRID	16		2.6826	.0	-3.0480				
120-	GPID	17		2.6248	.0	-3.0511				
121-	GPID	18		2.6169	.0	-3.0541				
122-	GRID	19		-5.8679	2.75	4.7947				
123-	GRID	20		-5.8765	2.75	3.8675				
124-	GRID	21		-1.2816	2.264	2.2568				
125-	GPID	22		-2.3885	2.352	1.1258				
126-	GRID	23		1.0659	1.478	-0.2931				
127-	GPID	24		.2537	1.448	-1.1398				
128-	GRID	25		3.1984	.4638	-3.2936				
129-	GPID	26		3.1802	.4687	-3.3093				
130-	GRID	27		-5.2995	6.7	3.5979				
131-	GRID	28		-5.4958	6.7	3.2679				
132-	GPID	29		-5.6920	6.7	2.9379				
133-	GPID	30		-3.7187	5.7	2.0249				
134-	GRID	31		-4.2387	5.7	2.1323				
135-	GRID	32		-2.1279	4.7	2.2598				
136-	GRID	33		-2.4567	4.7	1.7932				
137-	GPID	34		-2.7956	4.7	1.3266				
138-	GRID	35		-0.6784	3.825	1.0824				
139-	GRID	36		-1.3024	3.825	.2589				
140-	GPID	37		.7712	2.95	-0.0950				
141-	GPID	38		.4750	2.95	-0.4520				
142-	GPID	39		.1906	2.95	-0.8089				
143-	GRID	40		2.1004	2.075	-1.6943				
144-	GRID	41		1.7981	2.075	-2.0585				
145-	GPID	42		3.4295	1.2	-2.2986				
146-	GPID	43		3.4226	1.2	-3.3009				
147-	GRID	44		8.4156	1.2	-3.3081				
148-	GRID	45		-4.4900	9.3875	2.6427				
149-	GPID	46		-4.7608	9.3845	2.1181				
150-	GPID	47		-1.5712	6.875	1.5336				

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Figure A.4 (Continued)

ΓΓΓ PROPELLER DYNAMIC RESPONSE
PARTIALLY SUBMERGED PROPELLED

TIPOGY TRANSIENT RESPONSE

S O R T E D   B U L K   D A T A   E C H O

	1	2	..	3	..	4	..	5	..	6	..	7	..	8	..	9	..	10	..
CARD COUNT	.																		
151-	GRID	48		-2.0210		6.875		.8396											
152-	GRID	49		1.1270		4.425		-0.4123											
153-	GRID	50		.7080		4.425		-0.9710											
154-	GRID	51		3.6073		2.2		-5.1171											
155-	GRID	52		3.5998		2.2		-5.1267											
156-	GRID	53		-2.7381		11.45		1.4487											
157-	GRID	54		-2.8052		11.45		1.3046											
158-	GRID	55		-2.8772		11.45		1.1605											
159-	GRID	56		-1.8763		10.25		1.1280											
160-	GRID	57		-2.0644		10.25		.7565											
161-	GRID	58		-1.0145		9.05		.8073											
162-	GRID	59		-1.1355		9.05		.5799											
163-	GRID	60		-1.7565		9.05		.3325											
164-	GRID	61		.2351		7.475		.0380											
165-	GRID	62		-0.0106		7.475		-0.3903											
166-	GRID	63		1.4866		5.9		-0.7295											
167-	GRID	64		1.76		5.9		-0.9313											
168-	GRID	65		1.2353		5.9		-1.1331											
169-	GRID	66		2.5706		4.55		-1.4023											
170-	GRID	67		2.8424		4.55		-2.0091											
171-	GRID	68		3.6566		3.2		-2.8760											
172-	GRID	69		3.6531		3.2		-2.8801											
173-	GRID	70		3.6495		3.2		-2.8851											
174-	GRID	71		-1.8321		11.615		.9761											
175-	GRID	72		-1.9348		11.615		.7558											
176-	GRID	73		-0.1190		10.0		.2206											
177-	GRID	74		-0.2416		10.0		-0.0105											
178-	GRID	75		2.1855		6.55		-1.2028											
179-	GRID	76		2.0591		6.55		-1.4081											
180-	GRID	77		3.5602		4.2		-2.5836											
181-	GRID	78		3.5541		4.2		-2.5931											
182-	GRID	79		-0.9260		11.78		.5034											
183-	GRID	80		-0.9617		11.78		.4273											
184-	GRID	81		-0.9974		11.78		.3511											
185-	GRID	82		-0.0747		11.365		.0687											
186-	GRID	83		-0.1121		11.765		-0.0117											
187-	GRID	84		.7766		10.95		0.8661											
188-	GRID	85		.7750		10.95		-0.3698											
189-	GRID	86		.7773		10.95		-0.3734											
190-	GRID	87		2.0526		9.2191		-1.0774											
191-	GRID	88		2.0491		9.2190		-1.0846											
192-	GRID	89		2.8864		7.2		-1.6761											
193-	GRID	90		2.8867		7.2		-1.6796											
194-	GRID	91		2.8829		7.2		-1.6830											
195-	GRID	92		3.1751		6.2		-1.9841											
196-	GRID	93		3.1708		6.2		-1.9921											
197-	GRID	94		3.6638		5.2		-2.2921											
198-	GRID	95		3.6612		5.2		-2.2966											
199-	GRID	96		3.6586		5.2		-2.3011											
200-	MAT1	50		16.0E6		.3		4.27-4											

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CES PROPELLER DYNAMIC RESPONSE
PARTIALLY SUBMERGED PROPELLER

DIRECT TRANSIENT RESPONSE

S O R T E D   B U L K   D A T A   E C H O

CARD COUNT	1	2	3	4	5	6	7	8	9	10
201-	PARAM	COUPMASS1								
202-	PTHEX	30	50			2000.		90.0		
203-	SPC1	18	155	117	2	122	125	130	183	149	+SPC11
204-	+SPC11	152	196	158	172	177	180	185	188		+SPC12
205-	+SPC12	193	248	212	215	218	221	235	240		+SPC13
206-	+SPC13	243	284	251	256	259	272	275	278		+SPC14
207-	+SPC14	281	284	289	297	297	300	305	308		+SPC15
208-	+SPC15	109	114								
209-	SPC1	18	1	123456	THRU	18					
210-	SPOINT	109	114	117	122	125	130	133	149		
211-	SPOINT	152	155	158	172	177	180	185	188		
212-	SPOINT	193	196	212	215	218	221	235	240		
213-	SPOINT	243	248	251	256	259	272	275	278		
214-	SPOINT	281	284	289	297	297	300	305	308		
215-	TABLED1	271									+T21
216-	+T21	8.	0.	3.4238-30.		3.4240-8	34.	3.8520-3	12.		+T211
217-	+T211	1.07-2	12.	1.071-2	0.	ENDT					
218-	TABLED1	223									+T23
219-	+T23	0.	0.	3.4230-30.		7.4240-7124.		5.2965-3	47.		+T231
220-	+T231	7.1690-8	37.	1.07-2	7.	1.071-2	0.	ENDT			
221-	TABLED1	247									+T47
222-	+T47	0.	0.	1.657E-30.		1.658E-3	34.	1.07-2	34.		+T471
223-	+T471	1.071-2	0.	ENDT							
224-	TABLED1	249									+T49
225-	+T49	8.	0.	1.6575-30.		1.6585-3153.		3.7985-3	78.		+T491
226-	+T491	5.9385-3	57.	1.07-2	57.	1.071-2	0.	ENDT			
227-	TABLED1	273									+T73
228-	+T73	8.	8.	0.4270-30.		0.4280-8251.		1.7655-3116.			+T731
229-	+T731	7.1030-3100.		1.07-2	100.	1.071-2	0.	ENDT			
230-	TABLED1	275									+T75
231-	+T75	0.	0.	0.4270-50.		0.4280-3233.		2.4610-3142.			+T751
232-	+T751	6.6060-3121.		1.07-2	121.	1.071-2	0.	ENDT			
233-	TLOAD1	20	173			273					
234-	TLOAD1	80	175			275					
235-	TLOAD1	40	147			247					
236-	TLOAD1	50	149			249					
237-	TLOAD1	60	121			221					
238-	TLOAD1	70	123			223					
239-	TSTEP	21	17	.05*5-? 1							
	ENDDATA										

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