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OTEC COLD WATER PIPE

A SURVEY OF AVAILABLE SHELL ANALYSIS COMPUTER PROGRAMS AND IMPLICATIONS OF HYDRODYNAMIC LOADINGS

PREPARED BY:
ORI, INC.

PREPARED FOR:
NOAA OFFICE OF OCEAN ENGINEERING
AS TASK ORDER 2.1
UNDER DEPT - OF COMMERCE CONTRACT
No. MO-A01-78-00-4137

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PREPARED BY:
ANALYSIS & TECHNOLOGY, INC.

PREPARED FOR:
ORI, INC. - SUBCONTRACT NO. 7047

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I. EXECUTIVE SUMMARY

The design and analysis of the cold water pipe (CWP) is one of the most important technological problems to be solved in the OTEC ocean engineering program. Analytical computer models have to be developed and verified in order to provide an engineering approach for the OTEC CWP with regards to environmental factors such as waves, currents, platform motions, etc., and for various structural configurations and materials such as rigid wall CWP, compliant CWP, stockade CWP, etc. To this end, Analysis & Technology, Inc. has performed a review and evaluation of shell structural analysis computer programs applicable to the design of an OTEC CWP. Included in this evaluation are discussions of the hydrodynamic flow field, structure-fluid interaction and the state-of-the-art analytical procedures for analysis of offshore structures.

The report is broken up into four sections. Section 1 describes the requirements of the Analysis & Technology, Inc. task effort and presents the overall conclusions and recommendations. Section 2, written by Kenneth M. Webman, describes the analytical procedures which must be incorporated into the design of a CWP. A brief review of the state-of-the-art for analysis of offshore structures and the need for a shell analysis for the OTEC CWP are included. Section 3 represents the bulk of the report and was written by Dr. Henno Allik. Included in this section is a survey of available shell computer programs, both special purpose and general purpose, and discussions of the features of these dynamic shell programs and how the hydrodynamic loads are represented within the computer programs. Section 4, written by Dr. Malcom L. Spaulding and Dr. Frank M. White describes the hydrodynamic loads design criteria for the CWP. An assessment of the current state of knowledge for hydrodynamic loads is presented.

The reader is referred to the sections of the report described above in order to fully understand the implications of the work effort performed and how it provides an engineering approach for the design and analysis of an OTEC CWP. However, for the reader who is not interested in such a detailed description of the work effort, a brief summary of the major conclusions and recommendations are now provided:

1. The OTEC community has used linear analysis in conjunction with various beam type models for the CWP. The only difference between these CWP analyses and the accepted state-of-the-art is that only linearized solutions (frequency domain) have been used for OTEC.

2. Based on material and geometric considerations, the CWP may behave like a shell and not like a beam. Shell analysis of the CWP will then have to be performed.

3. A shell analysis of the OTEC CWP will have to be performed using a decoupled approach. Incorporation of structure-fluid interactions will not readily lend itself to an engineering design approach procedure.

4. No available shell computer program meets all the requirements for a CWP shell analysis, but several of the reviewed programs possess most of the needed capabilities.

5. Development of preprocessor programs to represent hydrodynamic loads and generate damping and added mass matrices are essential. These preprocessor programs will interface with existing shell programs.

6. Conduct a more thorough evaluation of selected computer programs by reviewing documentation and executing benchmark problems. One program should be selected, needed modifications implemented and interfaced with the preprocessor programs.

7. Assemble an integrated system of preprocessors, analysis program and postprocessor programs. The analysis program might be based on an existing program, but efficient solution algorithms specialized for the CWP problems will be incorporated. This will provide an efficient engineering approach for the design and analysis of CWP problems.

8. Sufficient data exist to define the hydrodynamic loads for a preliminary OTEC CWP design assuming the CWP is a rigid structure.

9. Develop a series of conservative hydrodynamic loading scenarios to account for the magnitude, as well as frequency composition of the key forcing mechanisms of the CWP. In developing these load spectra, the CWP should be considered as a component of the total OTEC plant configuration.

10. Additional effort to define hydrodynamic loads for flexible structures may be wasteful until the selection of material and plant design configurations are made. If at that time a flexible structure is indicated, a detailed engineering investigation employing both experimental and analytical/numerical procudures should be performed to supplement the design.

II. ANALYTICAL PROCEDURES FOR OTEC COLD WATER PIPE DESIGN AND ANALYSIS

2.1 BACKGROUND

The review of shell structural analysis computer programs for application to the design of an OTEC cold water pipe would not be complete without a brief review of the state-of-the-art analytical techniques applicable to offshore structures in general, and to OTEC CWP structures in particular. This review is required in order to determine an engineering approach for the analysis of the OTEC CWP with regards to environmental factors such as waves, currents, platform motions, etc., and for various structural configurations and materials such as rigid wall CWP, compliant CWP, stockade CWP, etc. Based on these geometric and material considerations, the CWP may exhibit shell-like behavior. A shell model would therefore be necessary in order to ensure an adequate engineering approach for the OTEC CWP design.

2.2 STATE-OF-THE-ART FOR ANALYSIS OF OFFSHORE STRUCTURES

Almost all analysis of offshore structures (usually towers) uses some variation of the following equations of motion:

$$\left[M\right]\left\{\ddot{u}\right\} + \left[C\right]\left\{\dot{u}\right\} + \left[K\right]\left\{u\right\} = \left\{P(x,t)\right\} \tag{2-1}$$

where $[M]$, $[C]$ and $[K]$ are the structural mass, damping and stiffness matrices, $\{\ddot{u}\}$, $\{\dot{u}\}$ and $\{u\}$ are the strucural accelaration, velocity and displacement vectors, and $\{P(x,t)\}$ represents the space and time varying hydrodynamic forces. The hydrodynamic forces exerted on a body can be assumed to be composed of three parts:

(1) The force resultant of the pressure exerted by the undisturbed incident wave train on the stationary body in its mean position.

(2) The force resulting from the motion of the body computed as though it undergoes the same motion in calm water.

(3) The force resulting from the disturbance of the incident waves by the body occupying its mean position.

The pressure force F_p due to the wave field represented by (1) above, i.e., that portion obtained by neglecting the effect of body motions and diffracted waves, is called the Froude-Krylov force. It is equal to the resultant force obtained by integrating over the surface of the body the pressure which would exist at that location if the body were not present. For cylindrical structures having small diameter (D) to wave length (L) ratios, i.e. $D/L<0.05$, the Froude-Krylov force can be assumed approximately equal to zero.

Morison[1] separated $P(x,t)$ into two parts as follows:

$C_M\ddot{V}_F$ = inertial force with $\ddot{V}_F$ the fluid particle acceleration and C_M a function of displaced volume and an empirical inertia (added mass) coefficient.

$C_D\dot{V}_F$ = drag force with $\dot{V}_F$ the fluid particle velocity and C_D a function of projected area and an empirical drag coefficient.

These two forces are equivalent to (2) and (3) above and can be called the added mass force and the drag force respectively.

Morison originally proposed the above equations for use in determining forces on piles due to surface current. The underlying assumption is that wave motions are not affected by the presence of the structure or that the characteristic dimension of the structure is much smaller than the wavelength. For a commercial OTEC plant with a large diameter CWP the above assumptions may be questionable.

Since for a flexible structure the velocities and accelerations may be of the same order of magnitude as those for the wave particles, these relations are usually modified as:

$$\left\{P(x,t)\right\} = \left[C_M\right]\left\{\ddot{V}_F - \ddot{u}\right\} + \left[C_D\right]\left\{\left(\dot{V}_F-\dot{u}\right)\left|\dot{V}_F-\dot{u}\right|\right\} + \left\{F_p\right\} \tag{2-2}$$

Equation (2-1) can be rewritten as:

$$\left[M+C_M\right]\left\{\ddot{u}\right\} + \left[C\right]\left\{\dot{u}\right\} + \left[K\right]\left\{u\right\} = \left[C_M\right]\left\{\ddot{V}_F\right\} + \left[C_D\right]\left\{\left(\dot{V}_F-\dot{u}\right)\left|\dot{V}_F-\dot{u}\right|\right\} + \left\{F_p\right\} \tag{2-3}$$

This equation is non-linear due to the second term on the right hand side. In the time domain this non-linear equation is solved or is linearized before solution by neglecting $\dot{u}$ in comparison to $\dot{V}_F$. In the frequency domain solution or a nondeterministic (random) solution equation (2-3) is always linearized.

The available literature contains a plethora of papers[2] on the analysis of offshore platforms and towers. Solution of Morison's equation as presented above, either in the frequency domain (linear analysis) or in the time domain (non-linear analysis), is the accepted state-of-the-art for the analysis of offshore structures. The structural configurations analyzed are usually long slender piles and these are modeled as beams. To date, the OTEC community has used linear analysis (with loadings and equations similar to those presented above) in conjunction with various types of beam model formulations for the CWP, such as the finite element method[3] and the line integration method[4]. Coupling of the rigid platform with its loadings has been incorporated into the models in order to get the overall structural response of the CWP. Thus, the only difference between the CWP analyses performed to date and the accepted state-of-the-art is that only linearized solutions (frequency domain) have been used for OTEC.

2.3 SHELL ANALYSIS OF OTEC CWP

The structural analyses performed for OTEC configurations have all used beam type models to represent the CWP. Although the exact configuration and material for an OTEC plant CWP have not as yet been defined, the following are some of the CWP alternatives:

1) rigid CWP with joints
2) compliant CWP
3) stockade CWP
4) bottom mounted buoyant CWP

Based on the material and geometry of the configurations involved, the CWP may indeed behave like a shell and not like a beam. Even for a "rigid" type CWP (metallic or concrete structure), if the thickness of the pipe is significantly smaller than the diameter and length of the pipe (see Figure 2.1), the configuration will respond as a shell and exhibit breathing modes, bending modes and various circumferential modes (ovalling), i.e., the cross-sectional shape of the pipe deforms. If the CWP will exhibit these shell-like motions, then errors will be incorporated into the analysis if the CWP is modeled as beam. These factors become more critical for flexible materials such as rubber or polyethylene. The shell-like response must therefore be incorporated into the analysis in order to insure an adequate engineering approach to the design of an OTEC CWP.

Calculation of hydrodynamic forces for a shell model of an OTEC CWP will require a slight extension of the existing state-of-the-art. For beam type models force components due to pressure, drag and added mass are applied at individual points along the pipe centerline. For a shell model, however, these loads will have to be applied at the various nodal points used to model the shell in the circumferential direction (see Figure 2.2). While analytical procedures for determining these force components exist, they have not been applied to offshore structures since only beam type models have been used to date.

It should be noted that this type of analytical procedure is basically a decoupled approach since structure-fluid interactions are not incorporated into the analyses. Incorporating the structure-fluid interactions into the analysis would not readily lend itself to an engineering design approach procedure since the analysis would be much more costly and the techniques are not fully developed for the range of Reynolds numbers under consideration (see Section 4). However, this decoupled approach is a common procedure for structural analysis (see Section 3) and is considered a valid engineering approach for solving structural configurations under the influence of hydrodynamic loads.

SCHEMATIC DIAGRAM OF OTEC COLD-WATER PIPE

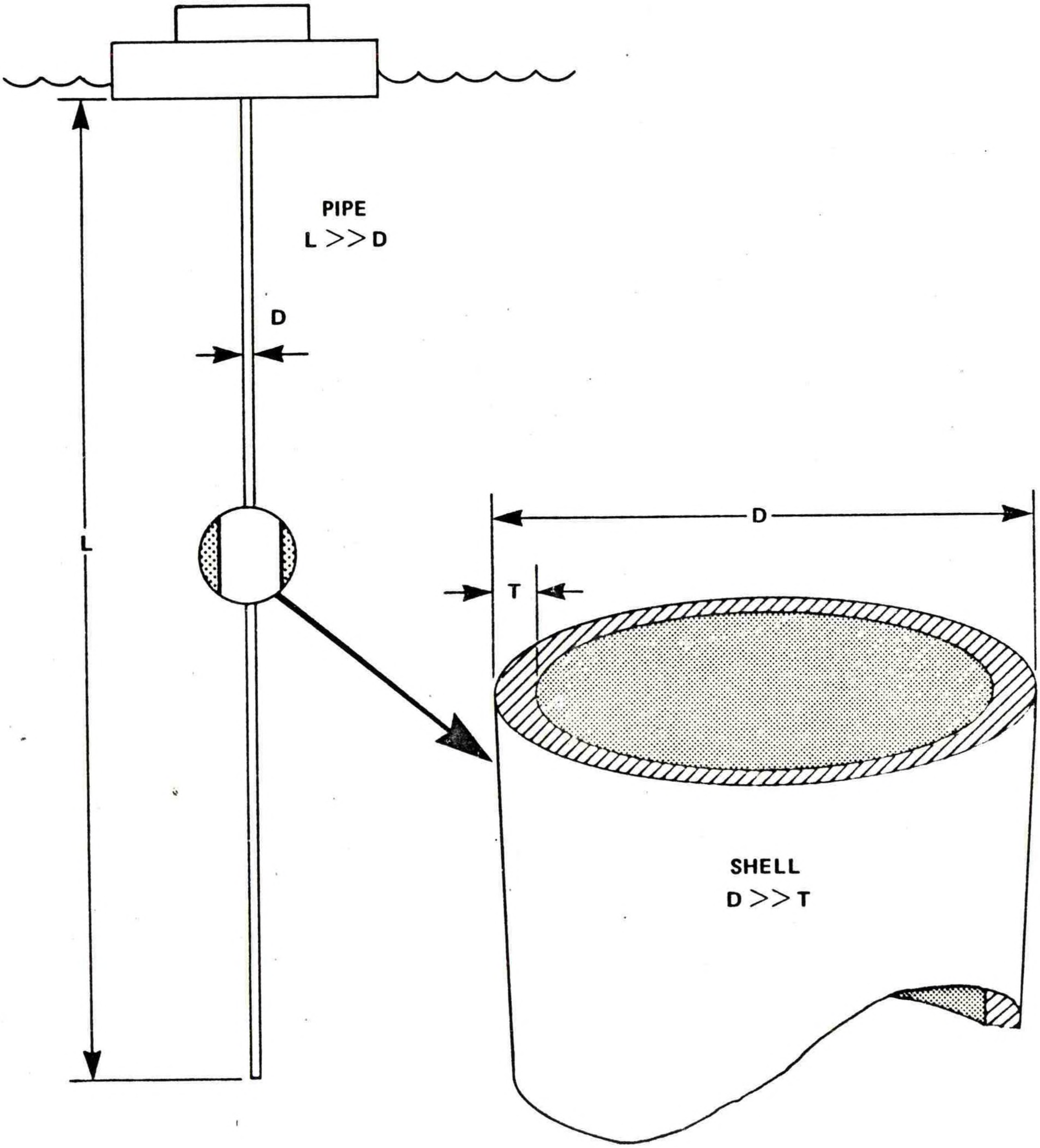


FIGURE 2.1

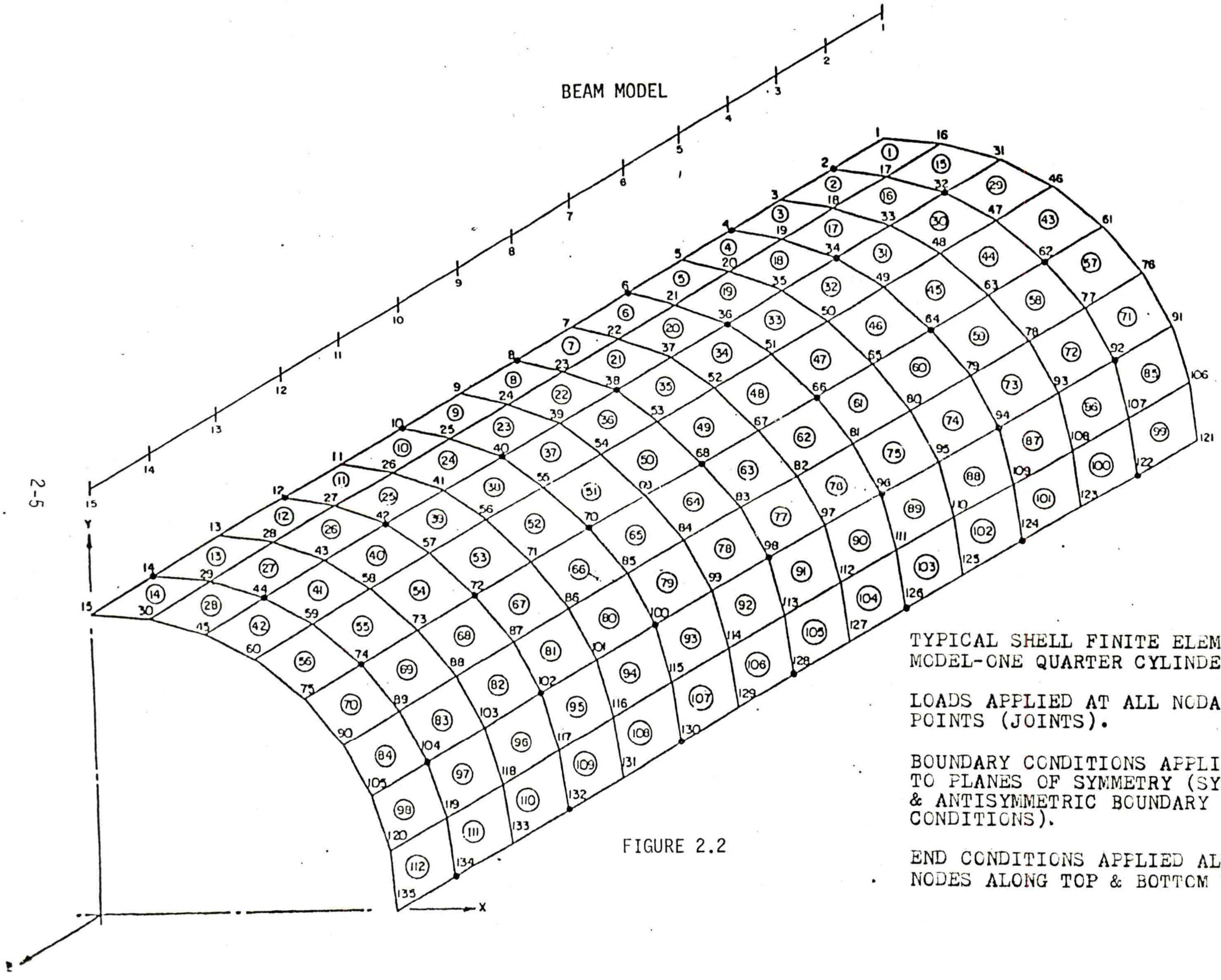


FIGURE 2.2

TYPICAL SHELL FINITE ELEMENT MODEL-ONE QUARTER CYLINDER.

LOADS APPLIED AT ALL NODAL POINTS (JOINTS).

BOUNDARY CONDITIONS APPLIED TO PLANES OF SYMMETRY (SYMMETRIC & ANTISYMMETRIC BOUNDARY CONDITIONS).

END CONDITIONS APPLIED ALL NODES ALONG TOP & BOTTOM EDGES.

III. REVIEW OF SHELL COMPUTER PROGRAMS FOR THE OTEC CWP

3.1 GENERAL FEATURES OF DYNAMIC SHELL PROGRAMS

Before proceeding to the discussion of specific computer programs available for the solution of dynamic shell problems it is pertinent to discuss some of the general features that distinguish one program from another. The CWP analysis problem is in some respects very specialized (e.g. cylindrical shell), but since many alternative design configurations are still under consideration, a program of quite general capabilities could be needed to handle all cases that arise. It will be helpful, then, to discuss some of the general program features, and point out their advantages and disadvantages in terms of potential CWP applications.

3.1.1 Shell Description

3.1.1.1 Arbitrary Shell Vs. Shell of Revolution

Shell codes may be divided into two categories; those that treat shells of arbitrary geometry and those that treat only shells of revolution. For the treatment of arbitrary shells the model is necessarily two-dimensional, while for shells of revolution it is possible to reduce the problem to a one-dimensional one. This is accomplished by expanding the circumferential coordinate in a Fourier series, which leads in the case of linear analysis, to a set of decoupled equations, one set for each Fourier harmonic. With the applied loading similarly expanded, it is possible to obtain completely arbitrary, three-dimensional response by superposition of the harmonics. For this approach to be effective the loading should not be discontinuous, for then a large number of harmonics need to be superimposed.

Since the CWP is in general axisymmetric and moreover the fluid loadings have generally a smooth variation, the shells of revolution approach appears to be an efficient means of solving the problem. Note however that the structural configurations as well as the boundary conditions have to be axisymmetric for this approach to be valid. For example, if the use of meridional (longitudinal) stiffeneers is contemplated, they have to be treated as "smeared". However, if these stiffeners are so far apart that significant variations of displacement or stress occur between them, then they cannot be averaged over the shell surface and have to be treated as discrete, thus violating the assumption of axial symmetry. Similar considerations apply also to boundary conditions, joints and any attached structure (e.g. mooring cables).

In non-linear analysis the equations do not, in general, uncouple as they do in linear analysis. Approximate solution techniques, however, have been successfully applied in non-linear problems, retaining most of the cost-effectiveness of the one-dimensional representation.

3.1.1.2 Methods of Discretization

The four methods used for spatial discretization in shell codes are: finite differences, finite difference energy method, forward integration and finite elements. Except for the forward integration method, these discretization techniques are applicable to both arbitrary shells and shells of revolution. In the forward integration method Fourier decomposition is used and then the shell is divided into segments in the meridional direction. The equations are integrated over each segment, in order, starting from one of the boundaries and matching boundary conditions at other boundaries. This approach is used in only a few special-purpose codes.

The conventional finite difference method generates algebraic equations from the differential equations of motion of the shell. Principal difficulties with this method are treatment of arbitrary boundary conditions and branched shells, as well as the generation of arbitrary meshes as might be required in areas of stress concentrations. Today this method has essentially been abandoned. The finite difference energy method was developed to overcome some of these problems. Finite differences are applied to the strain-displacement relations and then algebraic equations are obtained through energy principles and numerical integration over the shell. This method is used in two well-known and widely-used shell codes, STAGS and BOSOR, but it still doesn't approach the finite element method in generality of application.

The majority of shell codes are based on the finite element method. The shell surface is subdivided into a number of subregions or elements and displacements within each element are expressed in terms of polynomial interpolation functions. Properties of each element are obtained by applying energy or variational principles and integrating over the element surface. The resulting algebraic equations are "assembled" to obtain overall equilibrium equations of the structure. Hundreds of papers have been written in recent years on finite element shell analysis and many different element formulations are used in available shell codes. Primarily three shell representations are used: (1) "faceted" or flat elements where membrane and bending effects are uncoupled within each element, but coupled in the global assemblage, (2) specialization of isoparametric solid elements to yield curved, thick or thin shells and (3) curved elements formulated via classical shell theories. The use of flat elements introduces a physical approximation, which nevertheless yields acceptable results and generally at less expense than the more complex formulations.

Any of the discretization methods should be acceptable for the CWP problem. However, codes other than those employing the finite element method, tend to be extremely specialized and lack modeling capabilities such as stiffeners, general boundary constraints, etc. Also, since the finite element method is an active research area, codes that employ this method are likely to be more up-to-date, modular, easier to modify and more generally available.

3.1.1.3 Shell Theories

A variety of classical shell theories for both linear and non-linear shells are employed in shell computer codes. All of them attempt to make an intractable three-dimensional problem into a more tractable two-dimensional one. Most of these theories differ only in detail from the basic Love-Kirchhoff thin-shell assumptions, namely:

1. Thickness to characteristic shell dimension is much less than one.
2. Transverse normal stress is small compared to in-plane stresses and is therefore neglected.
3. Straight lines initially perpendicular to the middle surface remain perpendicular and straight during deformation.

Beyond these basic assumptions the differences between shell theories are not important in numerical solutions since with a fine enough grid all theories from deep, to shallow, to flat plate representation converge to correct solutions. The finite element method in fact dispenses with shell theories as such for element representations 1 and 2 as given in the previous section. The only assumption of possible importance to CWP analysis is assumption 3 above, which distinguishes a thin shell from a thick one. Several shell codes have capabilities for relaxing this constraint by allowing shear deformations in cases of thick shells with significant transverse shear stresses.

3.1.2 Equations of Motion

3.1.2.1 Linear Analysis. The governing equations of motion for a discrete shell can be written as:

$$[M]\{\ddot{u}\} = \{F_E\} - \{F_I\} \tag{3-1}$$

where $[M]$ is the mass matrix, $\{u\}$ represents the nodal displacement degrees-of-freedom (generally 6 - 3 displacements and 3 rotations), $\{F_E\}$ is the vector of externally applied forces and $\{F_I\}$ are the internal nodal forces of the structure.

For the present let us ignore the source of the loading and assume that $\left\{F_E\right\}$ represents discrete loads applied to the structure, whose magnitude is known as a function of the space and time coordinate.

For small displacement, linear elastic problems

$$\left\{F_I\right\} = \left[K\right]\left\{U\right\} \qquad (3\text{-}2)$$

where $\left[K\right]$ is the stiffness matrix. Substituting Equation (3-2) and the conventional representation of damping forces (viscous damping) into Equation (3-1) the equations of motion become

$$\left[M\right]\left\{\ddot{U}\right\} + \left[C\right]\left\{\dot{U}\right\} + \left[K\right]\left\{U\right\} = \left\{F_E\right\} \qquad (3\text{-}3)$$

Both non-diagonal (consistent) and diagonal (lumped) mass matrices are in common use. Consistent mass is obtained directly from energy principles "consistent" with the assumed displacement functions used for deriving the stiffness. Its use tends to over-estimate the frequencies and under certain conditions provides an upper bound to the exact frequencies. Lumped mass on the other hand, tends to underestimate frequencies. It has been suggested that consistent mass is not worth the added computational expense and this is undoubtedly true when explicit methods of time integration are used for solution. Many shell codes include both types of mass matrices. A point worth noting for CWP analysis is that if the use of an added mass matrix for fluid representation is contemplated, then the shell program should include the capability to treat non-diagonal mass matrices.

Damping representations are generally not derivable from equations of theoretical mechanics. Hence they are based either on physical assumptions such as viscous, hysteretic (material) or Coulomb damping, or on achieving tractable formulations, such as proportional damping and equivalent modal damping. The treatment of fluid-structure interaction in the CWP analysis will likely have an influence on the type of damping matrix needed.

The stiffness matrix is of course the way in which the discretization methods of the previous section enter the analysis. The details of its formulation, together with the solution technique used, determine the accuracy and speed of solution and hence the efficiency of the particular shell code.

3.1.2.2 Non-Linear Analysis. Non-linear problems are solved by some combination of incremental and iterative techniques. When these are coupled to solution methods for transient response numerous formulations are possible. Non-linearities are usually treated by either the tangential stiffness method, or by the pseudo-load method.

In the tangential stiffness method the equations are linearized at each time step so that the internal forces for use in Equation (3-1) are given by

$$\{F_I\ (u + \Delta U)\} = \{F_I\ (U)\} + [K_T]\ \{\Delta U\} \qquad (3\text{-}4)$$

where $[K_T]$ is the tangent stiffness valid only for small departures $[\Delta U]$ from the current displacement state $\{U\}$.

Both geometric and material non-linearities can be included in the tangent stiffness matrix and one possible way of expressing these in the finite element context is

$$[K_T] = \int_V [B]^T\ [D_T]\ [B]\ dV = [K\sigma] \qquad (3\text{-}5)$$

where $[B]$ represents the non-linear strain-displacement relations, $[D_T]$ is the linearized (tangential) constitutive matrix and $[K\sigma]$ is the initial stress or geometric stiffness matrix.

Depending on the specific structural configuration and material being analyzed several choices of formulation and simplifying assumptions are implied in the above equation. Some of the terms in the strain-displacement equations can be neglected for metal structures where small-strain but large rotation assumptions are valid. Large strains are usually included only for rubber-like materials. The constitutive constants might include elastic-plastic, strain-hardening behavior for steels, non-linear elastic properties for glass reinforced plastic (GRP), various material models developed for rubber, etc.

The initial stress stiffness matrix $[K\sigma]$ is also a geometric non-linearity and accounts for the stiffening or softening effect of membrane stresses on transverse stiffness. Even in the presence of small displacements these stresses can have a significant effect on the response (e.g. buckling, or the effect of tension on lateral vibrations of a plate). If these stresses are known a priori their effect can also be included in a linear analysis with the internal forces being written as

$$\{F_I\} = [K + K_\sigma]\ \{U\} \qquad (3\text{-}6)$$

where $[K]$ is the linear stiffness of Equation (3-2).

In the pseudo-load method the internal forces are expressed as

$$\{F_I\} = [K]\ \{U\} + \{Q\} \qquad (3\text{-}7)$$

where $\{Q\}$ is the pseudo-load which includes all non-linearities and is the difference between the actual forces and the linear forces. The advantage of this formulation is that when Equation (3-7) is substituted into Equation (3-1) and the pseudo-loads taken to the right-hand-side, then the equations are identical to the linear equations with an additional external force of $-\{Q\}$. Although this representation is not as exact as the tangential stiffness method and therefore requires smaller load or time steps for convergence, it has certain computational advantages as discussed in the next section.

Note that the pseudo-load method is the only way that the computational advantage of the Fourier decomposition of axisymmetric shells can be retained in the presence of non-linearities. The tangent stiffness cannot be decoupled, as mentioned in Section 3.1.1.1.

The representations of internal forces in Equations (3-4) or (3-7) are only approximations to the true internal forces and if no correction is applied the solution will drift from the true solution. At times this inaccuracy can be serious although it can be minimized by using smaller load or time steps. To compensate for this error some programs compute the actual internal forces at the end of the time step using the computed displacements. This in essence is an equilibrium check which computes residual forces or forces that are unbalanced by the sum of the inertia, external and internal forces. These residual forces can be applied as corrective forces in the next time step, or can in fact be applied in an iterative procedure within a given time step to eliminate the residual.

3.1.3 Methods of Solution

3.1.3.1 Time Domain vs. Frequency Domain. The solution for the dynamic response of the structure can be obtained either in the frequency domain or in the time domain. In frequency domain solutions, which are applicable only to linear problems, the equations of motion are first diagonalized (uncoupled) by using the frequencies and the mode shapes of the structure. The response of the structure can then be determined either by a response spectrum analysis or a stochastic analysis. In a response spectrum analysis the maximum response at each frequency is determined from the spectrum of input motion. The modal responses are then summed to obtain total response, usually in some root-mean-square sense, since all aspects of phasing are lost. Stochastic analysis is often used in offshore structures to determine the statistical properties of the response under wave loadings. The solution of the eigenvalue problem for the frequencies and mode shapes can be the most time-consuming part of the problem, especially for large (more than several hundred degree of freedom) models.

In time domain solutions the equations of motion are integrated numerically in time to obtain the response. Both modal superposition and direct integration of the simultaneous equations are used. Modal superposition is again limited to linear problems where the equations are first diagonalized using the solution of the eigenvalue problem. Selected uncoupled equations, generally in the lower end of the spectrum, are then integrated and the results superimposed.

It would appear that with non-linearities relegated to the right-hand-side of the equation, as in Fourier analysis of axisymmetric problems, modal methods could also be applied to non-linear problems. Some papers on this approach have recently appeared in the literature, but no available shell program currently employs this method. Instead, all non-linear shell programs integrate the equations directly using either explicit or implicit time integration techniques.

3.1.3.2 Calculation of Eigenvalues. Besides their use in diagonalizing the equations for response computation, eigenvalues are of importance also in the design of the structure, e.g. insuring that the natural frequencies of the shell are removed from possible excitation frequencies. Two types of eigenvalue extraction methods are in common use. The transformation or direct methods (e.g. Householder, Givens) transform the matrices into tri-diagonal or diagonal form so that all the eigenvalues can be computed. Since these calculations are generally performed in-core, these methods are limited to relatively small systems (300-400 dof). For that reason the eigenvalue extraction is generally preceded by condensation, where some degrees-of-freedom (such as rotational dof) are eliminated to yield a smaller system of equations. Guyans reduction may be used on both the mass and stiffness matrices, but a non-diagonal mass matrix always results (even if it was originally diagonal). Alternately the stiffness may be reduced by static condensation and masses simply assigned to the remaining degrees-of-freedom.

The other method of eigenvalue determination involves vector iteration and is used on large systems where only a few eigenvalues are desired. Theoretically all eigenvalues could be computed by these methods but it would be uneconomical to do so. Methods in common use include inverse power iteration with shifts and subspace iteration.

A difficulty in shell problems is that the predominant bending frequencies and membrane frequencies are far removed from each other, such that significant membrane modes appear at higher frequencies than insignificant bending modes. Also the frequencies tend to be clustered. This makes selective computation or frequencies difficult in that close frequencies are hard to separate and significant ones might be missed. Transient shell problems are also especially difficult since a large number of frequencies may be excited and thus have to be included in the analysis.

3.1.3.3. Numerical Integration Methods. The direct integration of the coupled equations of motion in shell codes is accomplished without first uncoupling the equations by modes. Two major classes of methods are used, namely implicit integration and explicit integration. Implicit methods require the solution of simultaneous equations in every time step to advance the solution. Generally for time t + Δt displacements are solved from

$$\left[K_{eff} \right] \left\{ U \; (t + \Delta t) \right\} = \left\{ F_{eff} \right\} \qquad (3\text{-}8)$$

3.2 SURVEY OF AVAILABLE SHELL PROGRAMS

Shell analysis capabilities are available in numerous computer programs that can be categorized as general purpose and special purpose programs. General purpose programs are applicable to a wide variety of structures, continua and types of analyses while special purpose programs are restricted to one or two classes or problem. A summary of computer program characteristics is presented in Figure 3.1. For the purposes of this survey, the minimum requirement was the capability to compute the dynamic response of shell structures. The shell geometry could be restricted to axisymmetric, but the loading and response had to be arbitrary.

Appendix 1 lists the available programs in both the general and special purpose categories together with a detailed list of program features and attributes. Most of the features have been discussed in the previous section. Others simply provide more information on types of material, types of loads, pre- and post-processors, etc. available in a particular program. This information was gathered from a variety of sources, such as user's manuals and brochures, but much of it was compiled from various reviews of computer programs in References 5 and 6. Since many of these programs are under continual development, it is possible that some of the information is out of date. Appendix 2 lists the sources for these programs.

3.2.1 General Purpose Programs

A summary of capabilities for the most generally available and most widely used general purpose programs is given in Table 3.1. All are based on the finite element method and contain extensive libraries of different element types. Most of these programs are under continuous development and hence tend to provide similar capabilities that differ only in detail. The exception being non-linear capabilities, which are available in only four codes: MARC, ANSYS, NEPSAP and ADINA.

NASTRAN is probably the most powerful system for solving large-scale, linear problems. It is available on most major computer networks and many companies have in-house versions. COSMIC maintains and distributes the latest NASA-developed version, of the program, but NASA has discontinued further development. MacNeil-Schwendler Corp. is continuing with the development of MSC-NASTRAN and leases that version of the program. The shell element (faceted) in the COSMIC version is dated and not very accurate; a much better one is available in the MSC version. The MSC version also contains improved eigenvalue extraction capabilities. An initial stress or geometric stiffness matrix is available, but cannot be updated as stresses change.

SAPIV was developed at the University of California, Berkeley by Bathe and Wilson but they don't maintain it. It is the only large-scale program that is truly nonproprietary and is available for $250 for documentation and tape. The program architecture is easily comprehended and hence many locally modified versions of the program exist. A faceted element of good accuracy is used for shell analysis. Only a lumped mass matrix is available and eigenvalues can be obtained only by a subspace iteration method.

	GENERAL PURPOSE	SPECIAL PURPOSE
Problem Size	Unlimited	Limited
Solution Methods	Choice of Several	One
Structural Modeling	General	Limited
Implement Unique Solution Procedures	Yes	No
Interface with Pre- and Post-Processors	Good	Poor
Analysis Cost	High	Low
Ease of Usage	Difficult	Easy
Proprietary	Yes	No
Aquisition Cost	High	Low
Availability on Computer Network	Yes	No
User Support Available	Yes	No
Modify Program	Difficult	Easy

FIGURE 3.1. GENERAL COMPUTER PROGRAM CHARACTERISTICS

TABLE 3.1

SELECTED GENERAL PURPOSE PROGRAMS FOR DYNAMIC RESPONSE OF SHELL STRUCTURES

Program	Type	Analysis Type				Time Integrat.		Non-Linearity		Eigen-values		Proprietary	Service Bureau Use	Computer
				Transient										
		Spectrum	Random	Modal	Direct	Implicit	Explicit	Geometric	Material	Direct	Iteration			
ADINA	All Finite Element	-	-	-	X	X	X	X	X	-	X	X	?	ICU
ANSYS		X	X	X	X	X	-	X	X	X	-	X	X	ICU
MARC		-	X	X	X	X	X	X	X	-	X	X	X	ICU
NASTRAN		X	X	X	X	X	-	-	-	X	X	-	X	ICU
NEPSAP		-	-	-	X	X	-	X	X	X	X	X	?	ICU
NISA		X	X	X	-	X	-	-	-	X	X	X	X	CU
SAP IV		X	-	X	X	X	-	-	-	-	X	-	-	ICU
STARDYNE		X	X	X	-	X	-	-	-	X	X	X	X	C
STRUDL II		X	-	X	-	X	-	-	-	X	X	-	X	IU

Key:
X = yes
- = No

I = IBM
C = CDC
U = UNIVAC

STRUDL II is a widely used program in the Civil Engineering field, but mostly for beam/frame structures. The program was developed at MIT as part of the ICES system, but further development has been discontinued. The faceted shell element in the program is out-of-date and is inconvenient to use (membrane and bending elements have to be superimposed by the analyst). ICES-STRUDL is reported to be quite inefficient and hence expensive to use. A more efficient, completely new dynamic part of the program is available in DYNAL, which is a proprietary version of the program on the McAuto Computer Network. No direct numerical integration is available.

STARDYNE is another linear analysis program that is highly regarded by users for its reliability, economy and ease of usage. It is a proprietary program, but is available on CDC Cybernet computer network. A faceted shell element is used, only lumped mass is used and no direct integration is available.

NISA is a newer, proprietary program that is available on several computer networks. It has a large library of thick and thin shell elements of various orders, based on curved isoparametric formulation. No direct integration is available.

MARC is a proprietary program with the most complete and sophisticated non-linear capabilities of any code. It is available on CDC Cybernet. The shell elements are curved, higher-order elements that retain displacement derivatives as degrees of freedom in addition to the basic six displacement/rotation components. Since the derivatives are in the shell curvilinear system, elaborate tying features are needed for intersecting shells, attached stiffeners, etc. It is questionable, especially in dynamic problems, whether these additional degrees-of-freedom are worth the extra computational effort. The code is relatively expensive and difficult to use and hence is not often used in linear analysis.

ANSYS is the other generally used non-linear code. Its methods are not as sophisticated as those in MARC. A faceted shell element is used and for non-linear analysis no equilibrium check is provided. Many users prefer ANSYS over MARC for ease or usage and the program is widely used for both linear and non-linear analysis. ANSYS is proprietary, but is available on several computer networks.

NEPSAP is a proprietary Lockheed program that has been developed rather recently for non-linear analysis. The shell element is a non-linear version of the faceted element used in SAP.

ADINA is another recently developed non-linear code (by Bathe at MIT). It is an extension of a smaller program NONSAP developed at Berkeley. A shell element will be included in an upcoming release of the program (December, 1978) and hence its performance is currently unknown. The program has been included in this survey merely because it presents an alternate to the three rather expensive programs available for non-linear analysis. Although the program is proprietary it is available for $10,000. It is also the only one of the three that could possibly be modified by someone other than the developer (judging by the author's success in modifying NONSAP).

3.2.2 Special Purpose Programs

A comparison of capabilities for selected special purpose codes is provided in Table 3.2. The finite-difference codes have not been included, since they are too restricted, allowing for example, no stiffeners and limited boundary conditions. The following four codes use a one-dimensional representation of the shell with a Fourier series representation in the circumferential direction:

DYNAPLAS is a finite element code of the SOR family. SAMMSOR evaluates the stiffness matrix, FAMSOR extracts eigenvalues and DYNASOR and DYNAPLAS perform the transient response for linear and non-linear problems, respectively. Eigenvalues are extracted by inverse iteration. Both implicit (Houbolt) and explicit (central differences) numerical integration is available. Neither equilibrium checks or energy-balance is included. The program is well-documented and widely used. Problem size is limited by available core and depends on a combination of the number of elements and number of harmonics used in the problem.

SABOR/DRASTIC-6 is also a finite element program with capabilities very similar to those of DYNAPLAS.

KSHEL is a linear forward integration code. Eigenvalues can be computed by inverse iteration or determinant plotting. Transient response is performed by modal superposition. Ring stiffeners are simulated by short cylindrical shells.

STARS also uses forward integration. Material non-linearity (elastic-plastic) is included but geometric non-linearity is available only under axisymmetric loads. Eigenvalues are computed by a direct (Householder) technique and implicit (Houbolt) time integration is used.

The remaining four programs use a two-dimensional representation of the shell and only SLADE-D is restricted to a shell of revolution geometry. STAGS B uses the finite difference energy method while the other three use finite elements.

STAGS B is a non-linear code with the capability for solving very large shell problems. It has been under development and in use for a number of years. Both implicit and explicit time integration is available, as well as eigenvalue extraction capability. A new version of STAGS is to be released early in 1978. This version will have a faceted shell element similar to that used in SAP and NEPSAP but with a higher-order membrane. A beam stiffener will also be available.

TABLE 3.2

SELECTED SPECIAL PURPOSE PROGRAMS FOR DYNAMIC RESPONSE OF SHELL STRUCTURES

Program	Type	Geometry		Analysis			Time Integr		Non-Linearity		Eigen-values		Proprietary	Service Bureau Use	Computer
					Transient										
		General	Axisymmetric Arbit. Load	Spectrum Random	Modal	Direct	Implicit	Explicit	Geometric	Material	Direct	Iteration			
DYNAPLAS	FE	–	X	–	–	X	X	X	X	X	–	–	–	–	ICU
KSHEL	FI	–	X	–	X	–	?	?	–	–	–	X	–	X	ICU
SABOR/ DRASTIC	FE	–	X	–	–	X	X	–	X	X	–	–	–	–	IC
SLADE-D	FE	–	X +	–	–	X	–	X	–	–	–	–	–	–	C
STACS B	FDE	X	–	–	–	X	X	X	X	X	–	X	–	–	CU
STARS	FI	–	X	–	–	X	X	–	–	X	X	–	–	–	IU
TRAINS	FE	X	–	–	–	X	X	–	X	X	–	–	–	–	C
WHAM	FE	X	–	–	–	X	–	X	X	X	X	–	–	–	ICU

Key: FE – Finite Element

FDE – Finite Difference Energy

FI – Forward Integration

X = yes

– = no

I = IBM

C = CDC

U = UNIVAC

+ uses 2D representation

SLADE D is a linear finite element code for shells whose surface is a portion of an axisymmetric surface. Only explicit time integration is available and there is no eigenvalue capability. The time step is computed automatically.

TRAINS is a new non-linear finite element code for underwater shock analysis using implicit time integration. It uses the DAA (doubly asymptotic) method for representing a compressible fluid which includes an added mass matrix. The code can also be used without considering fluid effects. TRAINS is based on an earlier version of the MARC program and hence contains the same shell elements (see discussion under MARC). An energy balance check is included. The program is too new to have seen much use, but reportedly it is somewhat inefficient.

WHAM is a non-linear finite element code. Shells are modeled with faceted elements; beam stiffeners are included; rigid bodies and linkages are available. Explicit time integration is used and energy balance checks are made. Some rather large problems have been solved and the code is said to be efficient.

One additional special purpose, non-linear shell code that might be mentioned here is BOSOR 4. Although it has no transient analysis capability, it can be used for extracting eigenvalues. It is based on the finite difference energy method and can treat axisymmetric shells with discrete stiffeners in the circumferential direction. The inverse power method with shifts is used for calculating eigenvalues.

3.2.3 Comparison of General and Special Purpose Programs

A general comparison of program characteristics is presented in Table 3.3. Primarily what the table shows is that general purpose codes are readily available on computer networks, provide a wide range of capabilities, but cannot easily be modified. Special purpose programs have to be installed at the user's computer facility and, although capabilities are more limited, these codes are more easily modified for the user's specific needs.

Special purpose programs, having been designed to solve a special class of problem, should be more cost effective to use. However, the only way to determine a program's efficiency is through the execution of benchmark problems.

As far as modeling CWP structures is concerned, all of the general purpose codes should be able to model any configuration that is contemplated. Coupling of the platform and CWP, weighted end conditions, mooring systems, various joint conditions, etc., can all be represented. This is not the case with special purpose codes. They often don't have capabilities for attaching discrete masses, cables, springs, etc. Hence, modification of these programs is probably necessary. One possible way of treating the platform interaction is to input motions obtained from a coupled beam/platform analysis. This assumes that the shell modes do not modify the beam/platform

TABLE 3.3

COMPARISON OF PROGRAM CHARACTERISTICS

	GENERAL PURPOSE	SPECIAL PURPOSE
Problem Size	Practically unlimited	Might be limited; STAGS, WHAM and TRAINS practically unlimited.
Solution Methods		
Spectrum/Random	ANSYS, NASTRAN, NISA, STARDYNE	None
Integration	Implicit-all, explicit-ADINA & MARC	Implicit & explicit-DYNAFLAS, STAGS
Eigenvalues	All	KSHEL, STAGS, STARS, SCR Family
Non-Linear	ADINA, ANSYS, MARC, NEPSAP	All but KSHEL, SLADE, STARS
Structural Modeling	All have wide variety of elements, constraints, etc.	Limited capability; TRAINS, WHAM, new STAGS adequate
Availability		
Proprietary	All but SAP, versions of NASTRAN & STRUDL	None
Computer Networks	Most	None except KSHEL
Lease	Some	None
Acquisition Cost	$10K to $100K SAP $250	Varies from free to several thousand dollars

TABLE 3.3 - COMPARISON OF PROGRAM CHARACTERISTICS (Cont'd)

	GENERAL PURPOSE	SPECIAL PURPOSE
Maintenance/Support	Yes, by service bureau or developer, except SAP	In some cases by developer
Modifications to Program	Generally only by developer except SAP, ADINA	Local modification possible
Implement Unique Solution Procedure	Matrix language available in NASTRAN (DMAP), also SAMIS and MARTSAM from Appendix 1	Only through program modification
Pre- and Post-Processors		
Availability	Usually many available	Limited
Interfacing	Designed for interfacing	Probably need to modify program
Documentation	Voluminous, but generally adequate	Often quite involved

motions. Of course the loadings used in the two analyses have to be consistent. Most programs accept time-varying motions as input.

3.3 HYDRODYNAMIC LOADS REPRESENTATION

All of the programs included in this survey expect the loading to be specified as a function of spacial location and time. However, for a structure submerged in a fluid the surface forces are not known a priori but depend on the surface motion of the structure. This motion in turn influences the solution of the fluid field equations resulting in a coupled solution of the fluid field equations resulting in a coupled solution of the fluid-structure interaction problem (see Figure 3.2). Almost all the programs available for solving the coupled field equations have been developed for naval applications dealing with underwater shock and sonar problems. Consequently, the fluid field is limited to an acoustical representation. In fact, several of the general purpose programs included in this survey have been used for these programs included in this survey have been used for these problems, since three-dimensioned continuum elements, with appropriate constitutive constants, can be used to represent a fluid.

The solution of the coupled field equations is quite expensive. Hence, even for acoustic fluid problems, various surface approximations are used. These approximations eliminate the need for modeling the "infinite" fluid continuum thereby greatly reducing the size of the problem. For internal or contained fluids, finite element representations are still used. This method would be applicable to complaint CWP designs to determine water-hammer or bulge-wave effects due to shut-down or heave conditions. Currently much work is being done in implementing these methods, particularly the doubly asymptotic method, in structural computer programs. For example the TRAINS program included in this survey was developed expressly for this purpose. The importance of these developments to the CWP analysis is that the low-frequency response due to fluid inertia effects is represented in these methods by an added mass matrix. Hence, the computer codes developed for computing the added mass matrix for shell structures can also be used for computing the in-fluid frequencies as well as the transient response of the CWP structure.

Computer codes for the solution of coupled structure and Navier-Stokes equations are still in the research stage. There are several finite difference codes for the solution of highly non-linear continua problems which are applicable to both solids and fluids. These are however totally impractical for modeling structures, such as shells, since the whole idea of a shell representation is to avoid solving a continuum problem. It appears then that the state-of-the-art of offshore structural analysis is limited to approximate methods for representing fluid-structure interaction, much like the surface approximations used for acoustic fluid representations. Generally the interaction forces due to waves and currents are separated into three components: 1) time-varying pressures, 2) inertia forces and 3) drag forces. The latter two effects enter the structural equations as added mass and damping. A survey of current practice and computer programs used in

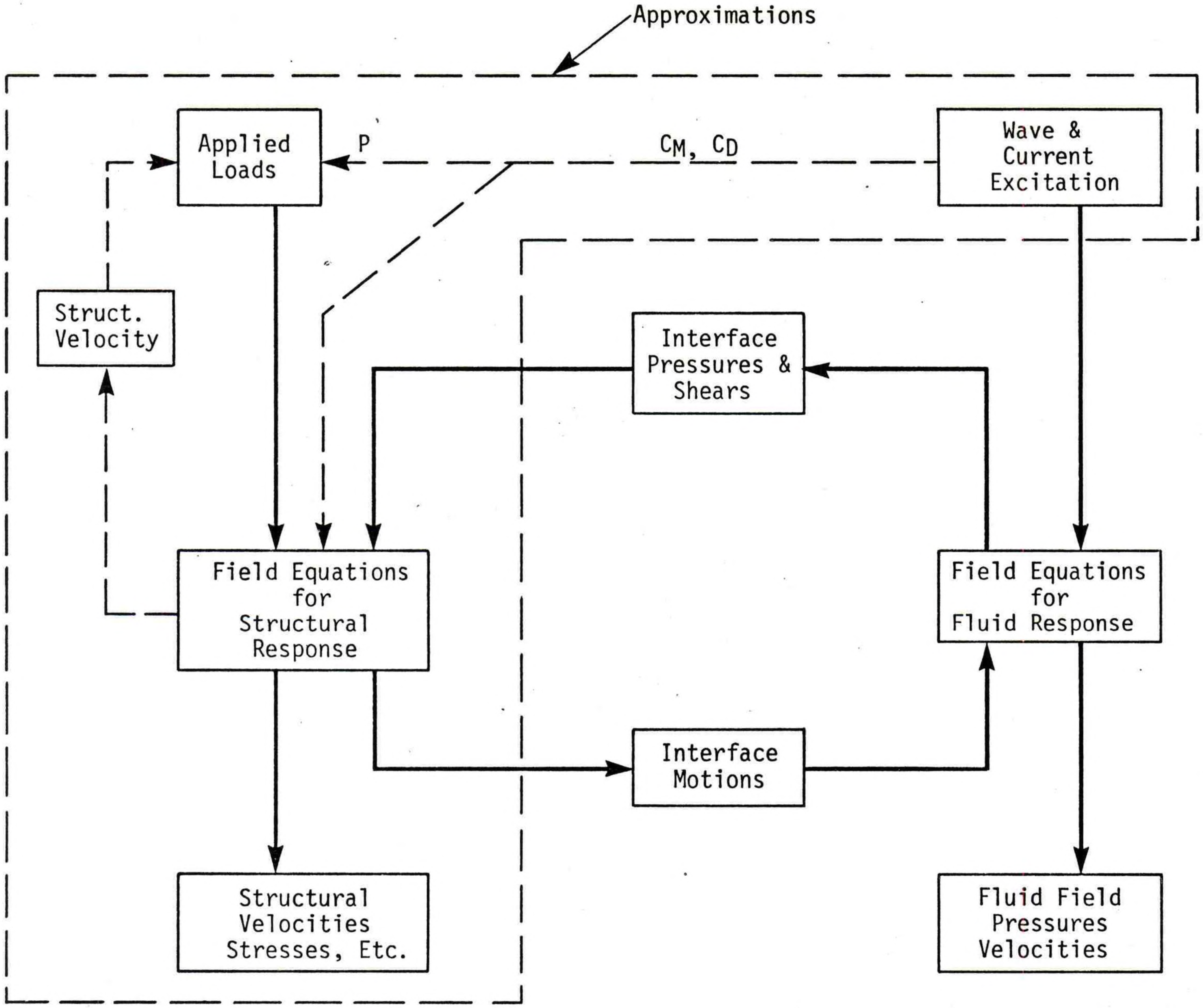


FIGURE 3.2. FLUID-STRUCTURE INTERACTION

offshore structures is available in Reference 7. Several well-known structural programs, such as STRUDL, NASTRAN and SAP, have been used in conjunction with hydrodynamic load generation programs to solve tubular structures such as towers or various types of platforms.

According to Reference 8 a generalization of these semi-empirical techniques can be used for hydrodynamic load representation on a shell model of the CWP. The greatest uncertainty in this approach appears to be for the case of highly flexible CWP configurations, responding either in the beam modes or in the shell modes, especially the latter. But short of attempting to solve the coupled field equations, there does not presently appear to be any improved representation available. Methods for interfacing the three-component (pressure, inertia and drag) representation with available shell codes is discussed in what follows. The details of computing the various empirical coefficients, or any improvement of these coefficients through additional testing, is unlikely to influence these considerations (see Section 4).

3.3.1 Time Varying Pressures

Most of the shell programs under consideration accept input pressures that can have arbitrary variation over the surface of the shell, with different loads having different time histories. However, the amount of data needed to represent hydrodynamic pressures makes it impractical to use these programs without a pre-processor for computing the loads automatically. This pre-processor should have capabilities for generating loads under various combinations of current, surface waves, internal waves, etc. Preferably, use should be made of the same geometrical information as is input to the structural model. The load generator could be specialized to a particular shell code, or could be written for general application, in which case interfacing with several programs is possible.

Most programs accept similar information except for the one-dimensional programs that require decomposition into Fourier harmonics. Some of the one-dimensional programs, e.g. DYNAPLAS, use only the cosine series expansion. This means that the loading as well as the response has to be symmetric with respect to the $\theta=0$ meridian. This assumption would be too restrictive for representing lift forces on the CWP as suggested in Reference 8. If the current is assumed to be symmetric with respect to $\theta=0^o$ on the CWP, then the lift component of the force would require terms in the sine series, since these forces are out-of-phase on opposite sides of the cylinder.

3.3.2 Added Mass

The proposed method for including the lift component of force due to currents requires the computation of in-fluid structural frequencies in order to determine whether they are within a certain percentage of the vortex shedding frequency, such as the 30% suggested by Science Applications, Inc. Therefore, added mass is required for frequency extraction as well as for transient response calculations.

Several methods as well as computer codes exist for computing added mass. Generally the boundary integral method for an ideal fluid is favored. A recent formulation developed at DTNSRDC has been incorporated in the TRAINS code. Another recent program (Reference 9) is part of the Underwater Shock Analysis (USA) code developed at Lockheed. USA also has an option for generating added mass for one-dimensional codes which require a different mass matrix for each Fourier harmonic. There should be little difficulty in interfacing an added mass routine with any program unless the program is limited to handling only diagonal mass matrices. General purpose programs, except SAP and STARDYNE should be able to accept such a matrix with no modification. Special purpose codes probably need modification. However, judging by the experience with DYNAPLAS these modifications are not extensive.

3.3.3 Hydrodynamic Drag

Drag forces can be represented as a damping matrix times the square of the difference between the wave particle velocity and the structural velocity. Since this expression is non-linear it is often linearized by various assumptions. Since general purpose programs all include viscous damping, linear damping can be included in them without difficulty, assuming that the terms of the damping matrix can be computed. Programs that include a matrix language, like NASTRAN's DMAP, could also be set up to handle non-linear damping. Most of the special purpose codes do not include damping, hence modifications would be necessary. For example, DYNAPLAS has been modified to include damping with its Houbolt integration scheme.

3.4 RECOMMENDATIONS

For the shell analysis of the CWP to be practical the development of pre-processors is essential, since an enormous amount of input data is required to represent hydrodynamic loads. Subroutines to generate the added mass matrix are available and need only to be interfaced with the shell program(s). Codes for generating the damping matrix and the various combinations and distributions of loads need to be developed.

No available shell code meets all the requirements of CWP shell analysis, but several of the reviewed codes possess most of the needed capabilities. The following three options are offered as possible ways of proceeding:

1. Use existing codes without modification

   NASTRAN most closely meets the analysis requirements of the CWP and is readily available. Its non-linear capabilities, however, are severely limited. For non-linear analysis MARC and ANSYS provide the most capability and are easily accessed through computer networks. Interfacing of pre-processors should be possible without modifying the programs.

2. Modify existing codes

   Conduct a more thorough evaluation of the capabilities and efficiency of selected codes. This should include a review of documentation and execution of benchmark problems. One code should be selected, the needed modifications implemented and interfaced with the pre-processors. Programs that should be included in this investigation are the one-dimensional codes DYNAPLAS and SABOR/DRASTIC and the two-dimensional codes STAGS (most recent version) and WHAM.

3. Develop an integrated program specifically for CWP Analysis

   Assemble an integrated system of pre-processors, analysis program and post-processor (results review, graphics) programs. The analysis code might be based on an existing code, but consideration should be given to implementing efficient solution algorithms that are specialized to the CWP problem.

It is recommended that option 2 be pursued first, followed by option 3 to obtain an efficient, user-oriented program that will be applicable also to future CWP designs.

IV. REVIEW OF HYDRODYNAMIC LOADS DESIGN CRITERIA FOR THE OTEC COLD WATER PIPE

4.1 BACKGROUND

Integral in the design of an OTEC floating power plant is the long slender pipe that brings cold water from ocean depths to the sea surface. While the plant may operate either held in place by an anchor or employ dynamic positioning systems, both operational modes subject this long cold water pipe to a wide variety of hydrodynamic loads. In addition to ocean currents, surface and internal waves as well as the flows induced by the OTEC plant itself must be considered in developing engineering design loads for the structural analysis of the cold water pipe.

One of the most important areas in the design of the OTEC cold water pipe (CWP) is a definition of these hydrodynamic loads. Many experiments and analytical investigations have been performed in this area. Science Applications, Inc. (SAI) has undertaken an extensive review of the available literature combined with a carefully selected series of experiments and analytical investigations to define the relevant hydrodynamic loads (Hove, Shih and Albano, 1978)[9]. Specifically, the study looked at circumferential pressure distributions, lift/drag coefficients, and the resultant load spectra for flow regimes typical of proposed OTEC sites. In addition, design procedures were also developed for both surface and internal wave effects, shear currents, and CWP internal flow dynamics. In an attempt to understand possible interactive coupling between the structure and the fluid, SAI applied the well known wake-oscillator model (Skop and Griffin, 1973)[10] for a linearly spring supported rigid cylinder to the OTEC CWP problem.

While the SAI report represents the most definitive effort at defining a detailed design procedure for the CWP, the interested reader is also referred to the recent texts by Blevins (1977)[11] and Denin (1975)[12] as well as the extensive bibliography contained in the SAI report.

The goal of this report is to review the extensive work performed by SAI and other available literature to determine its adequacy in defining the hydrodynamic loads for input to a shell model of the CWP. When examining the conclusions given here, it is important to note that the material properties and design of the pipe have a significant impact on the specification of the hydrodynamic loads. In general, as the pipe becomes more flexible and the interaction between the structure and the fluid increases, the task of specifying the hydrodynamic loads becomes more difficult. Since at present a range of materials (i.e., concrete, glass-reinforced plastic, steel, and rubber) and designs (flexible tubes, pipes and shells with/without stiffeners) are still under active consideration, this review has attempted to address the total range of hydrodynamic loads. Since the current OTEC prototype plant design employs a smaller diameter cold water pipe (approximately 30 feet) than the full scale plant (100 feet), the Reynolds number range of interest has been lowered and the design process made more difficult because of the increased influence of the laminar to turbulent flow transition. It has been assumed in the majority of the presentation that follows that the Reynolds number ranges are above transition values. This is a particularly critical assumption for vortex shedding forces, which exhibit a wide variety of responses through the transition region, and is very graphically illustrated in Figure 4.1.

Several additional studies funded by the NOAA Office of Ocean Engineering on CWP hydrodynamic loading are being performed. The results of these efforts may address many of the issues raised in the discussion that follows. Specifically, the efforts listed below (presented at a NOAA/DOE Technical Workshop on OTEC CWP Technology Development Program on January 17 and 18, 1978) should also be reviewed.

Organization	Title
Naval Research Lab.	Vortex Shedding and the OTEC CWP
Virginia Polytechnic Institute	Wind Tunnel Testing of Vortex Shedding from a Cylinder in a Shear Flow
University of Hawaii	Environmental Design Waves and Current Coupling Criteria

4.2 ASSESSMENT OF THE CURRENT STATE OF KNOWLEDGE

4.2.1 Hydrodynamic Loads

The three basic contributions to hydrodynamic loads on the OTEC system are from waves, currents, and power plant internal flows. Although each effect can be discussed separately, ultimately the limiting design conditions must account for coupling of all three, plus the associated coupled deformations and motions of the structure. Unlike the rather well defined equation formulation and solution procedures for the prediction of structural response, the specification of hydrodynamic loads are normally given as a combination of empirical relations based on experimental results and analytic investigations. Let us outline the present status of the separate mechanisms and then consider coupled interactions (Table 4.1 and 4.2).

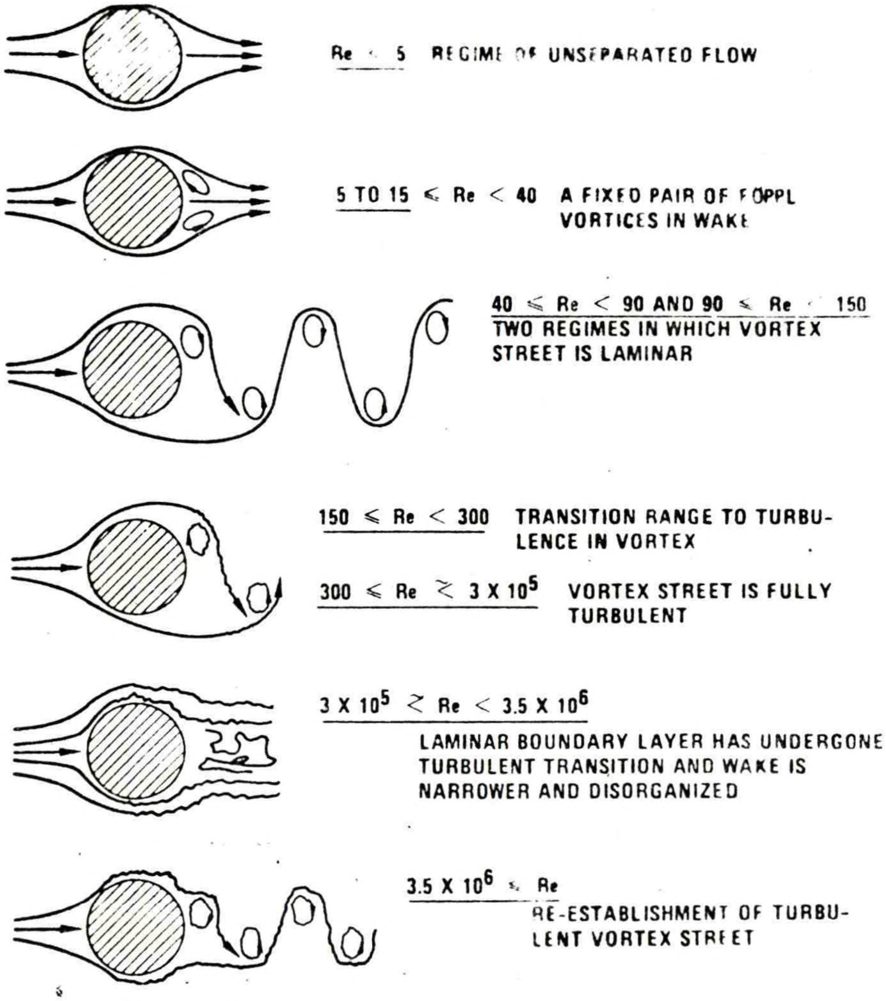


FIGURE 4.1. VORTEX SHEDDING PROCESS AS A FUNCTION OF REYNOLDS NUMBER (BLEVINS, 1977)

TABLE 4.1

ASSESSMENT OF THE CURRENT STATE OF HYDRODYNAMIC LOADS DESIGN METHODOLOGY

Hydrodynamic Loads	Inadequate for Preliminary Design	Adequate for Preliminary Design	Well Known and Tested Engineering Design Tool
A. Fluid-Structure Uncoupled			
1. Waves (Surface and Internal)			
a. Pressure			X
b. Drag		X	
c. Added Mass		X	
2. Currents			
a. Uniform-Steady			
C_p Pressure Distribution			
Mean			X
RMS		X	
C_D Mean			X
RMS		X	
C_L			
Peak	X		
RMS		X	
Spectral Content at Transition Re	X		
Spectral Content Above Transition Re		X	
b. Shear			
C_p Pressure Distribution			X
C_D			X
C_L	X		

TABLE 4.1 (Cont.)

Assessment of the Current State of Hydrodynamic Loads Design Methodology

Hydrodynamic Loads	Inadequate for Preliminary Design	Adequate for Preliminary Design	Well Known and Tested Engineering Design Tool
c. CWP Induced Flows Water Hammer			X
End Effects	X		
d. Coupled Motions Waves - Currents	X		
Internal Waves - CWP Induced Flows	X		
B. Fluid-Structures Interaction (Coupled) 1. Rigid Structure			
C_P		X	
C_D			X
C_L		X	
Rigid Structure Interaction Mechanism (Wake Oscillator Model)		X	
2. Flexible Structure			
C_P	X		
C_D	X		
C_L	X		
Flexible Structure Fluid Interaction Mechanism	X		

TABLE 4.2
PRIORITY OF RESEARCH NEEDS FOR OTEC FINAL DESIGN

1. Very Important
    - Wave - Currents Coupling
    - Flexible Fluid Structure Interaction

2. Moderately Important
    - Internal Waves - CWP Induced Flows
    - End Effects
    - Peak Current Lift Coefficient

3. Probably Not Important
    - Shear (Mean) Lift Coefficient
    - C_L Spectral Content at Transition Re Number

4.2.2 Current Loads

The relative motion of ocean currents past a bluff body such as the OTEC CWP will induce a hydrodynamic load which is primarily due to pressure differences around the body and only negligibly due to viscous forces. Thus, the most important quantity to be estimated is the surface pressure distribution (Figure 4.2) which has an oscillating component due to vortex shedding (Figure 4.3). The integrated pressure distribution results in a large drag force with a small oscillating component, plus a moderate-sized oscillating lift component. The local pressure distribution causes pipe deformation and possible interaction with pipe vibration phenomena. These vibration phenomena can include shell-like deformation of the pipe such as breathing modes, bending modes and various circumferential modes (ovalling). As outlined in Table 4.1, there is a great deal of data on hydrodynamic loads on rigid cylinders in a uniform current, especially the mean and r.m.s. pressure effects, but data is inadequate to fully describe the peak lift forces and the spectral content of the forces. Since ocean currents are the sum of tidal, Coriolis, wind-driven, and stratification effects, all of which are depth-varying, the typical current profile striking the OTEC CWP will be sheared and variable. Lift force data are lackinf for sheared profiles, especially at high Reynolds numbers. However, it is estimated that sheared profile effects will not have a strong influence on the design parameters.

If the structure is essentially rigid, its translation motions will interact with the flow in a manner that can be adequately described by an existing feedback analysis called the wake-oscillator theory (Iwan and Blevins, 1974)[13]. Using a simplified representation of the structure/flow field as shown in Figure 4.4, this technique employs a solution of an equation of motion for the structure coupled to a Van-der-Pol type equation representing the hydrodynamic loading. This theory is able to predict the force amplification which occurs during lock-in near the shedding frequency, but there is only moderate data on the pressure distribution (Denin, 1975)[12]. If the structure is highly flexible, its cross-sectional vibration modes will interact with the flow in an unknown manner. There is ver little data for such a case. If a flexible pipe is contemplated, the design should be preceded by a significant experimental study coupled with a non-linear extended wake-oscillation model. At lower Reynolds numbers, numerical modeling of flow past a deforming pipe is possible and may shed light on the interaction mechanisms (Hurlbut, Spaulding and White, 1978)[14].

4.2.3 Waves

Both surface and internal waves may induce fluid velocities and accelerations which cause forces on a submerged structure such as CWP. Internal waves can occur deep enough to affect the flow conditions at the CWP inlet, but their induced velocities are low. Their long periods, however, might excite vibration modes in the pipe.

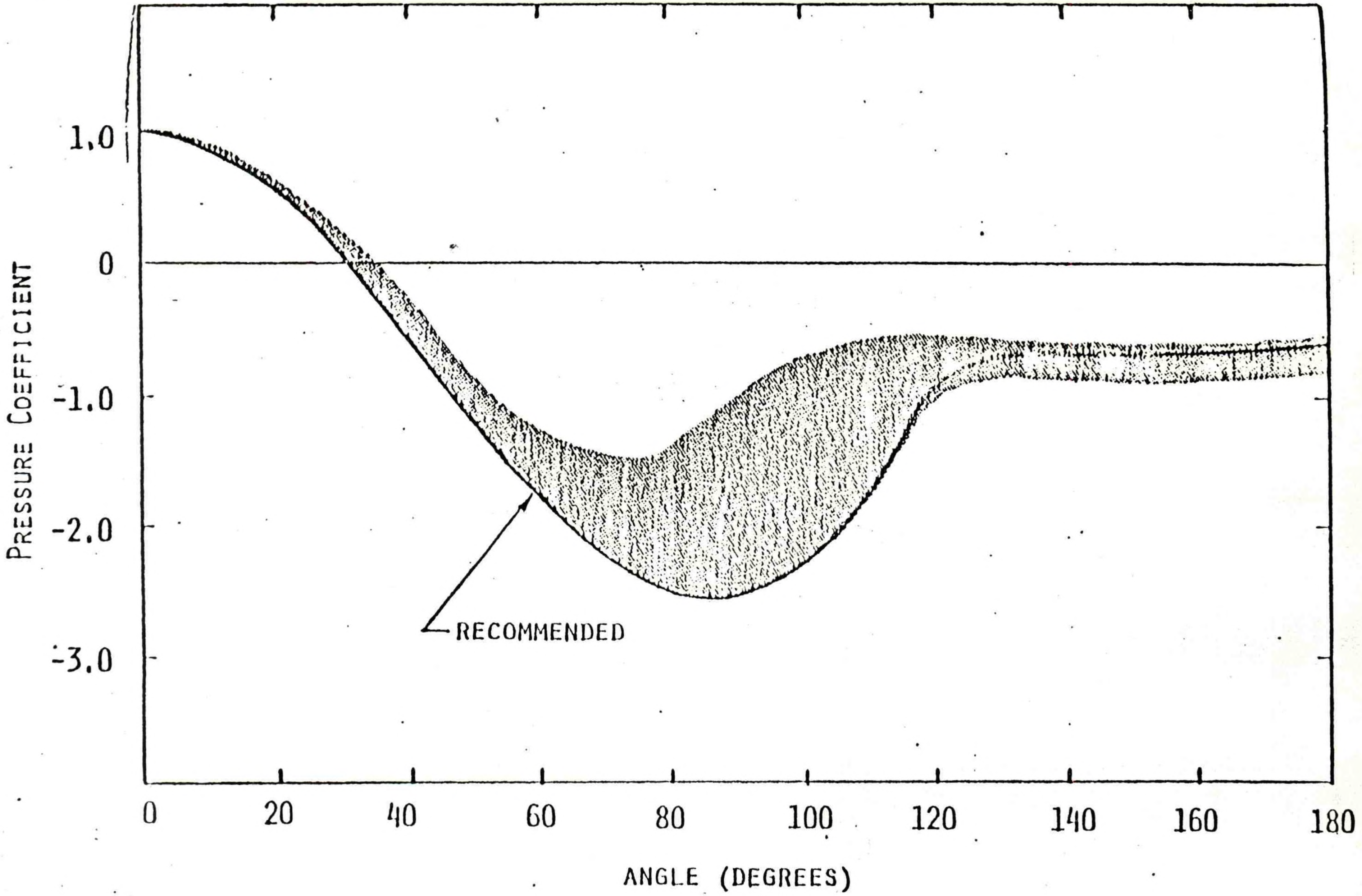


FIGURE 4.2. MEAN PRESSURE DISTRIBUTION (Hove, Shih and Albano, 1978)

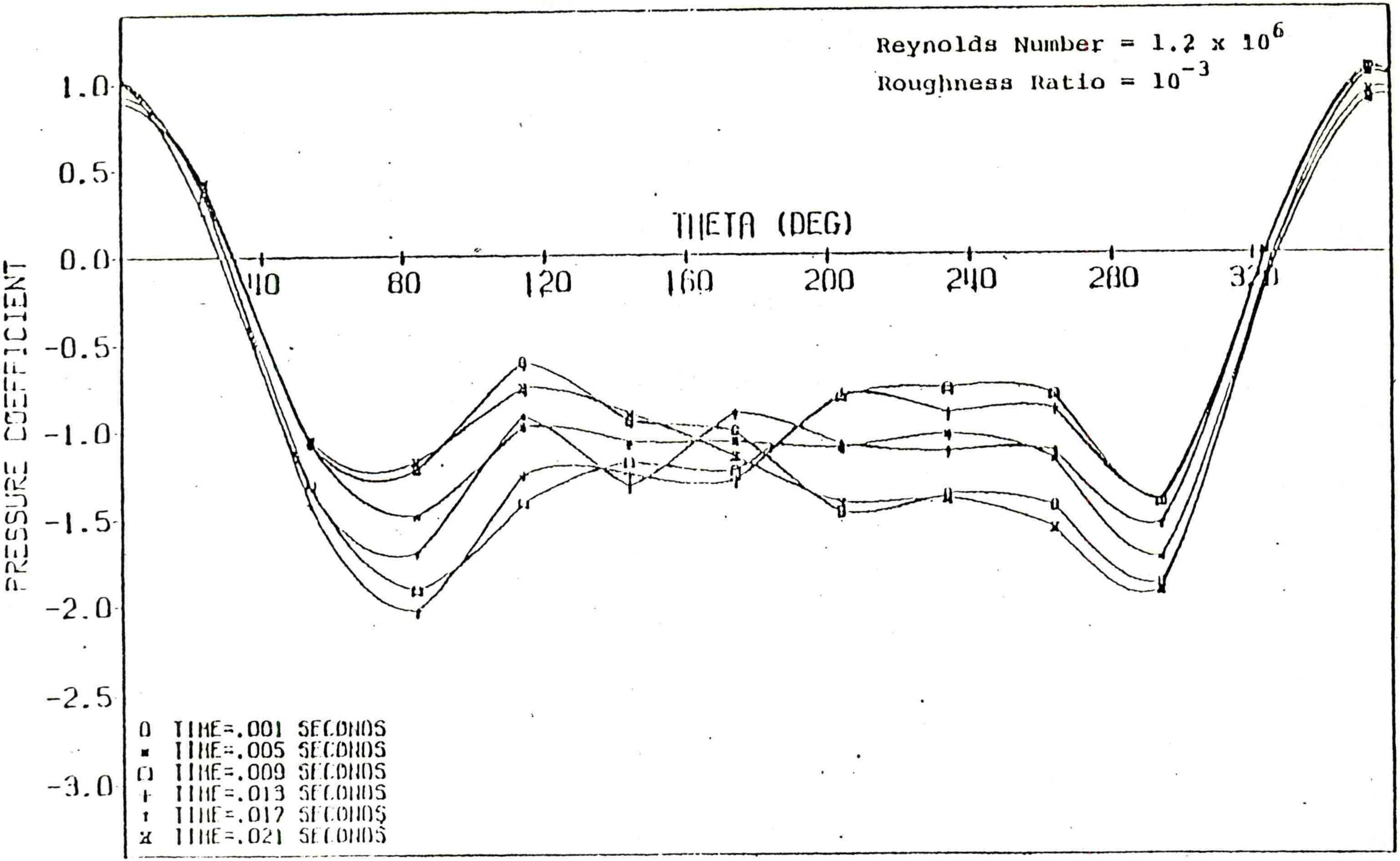


FIGURE 4.3. INSTANTANEOUS PRESSURE DISTRIBUTIONS SHOWING UNSTEADY COMPONENT CAUSED BY VORTEX SHEDDING (Hove, Shih, and Albano, 1978)[8]

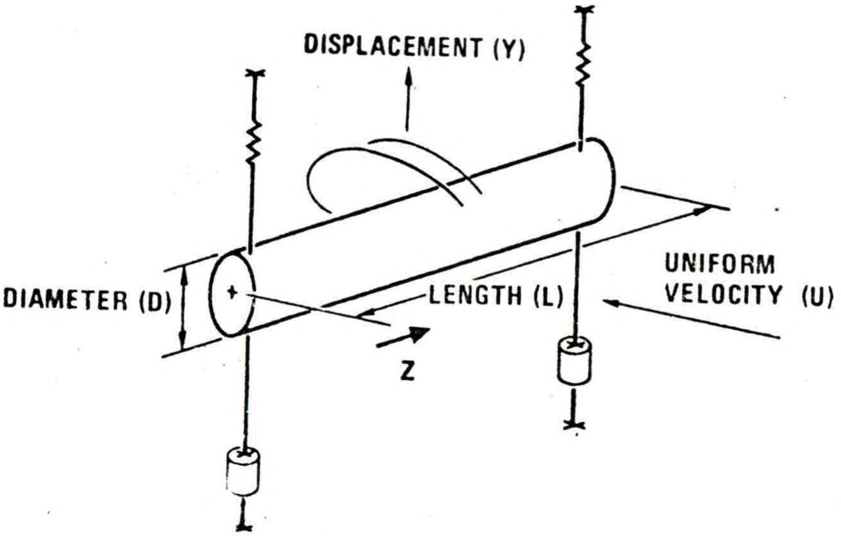


FIGURE 4.4. CYLINDER AND COORDINATE SYSTEM (RIGID CYLINDER MODE) FOR WAKE OSCILLATOR MODEL (Blevins, 1977)[11]

Surface waves are of shorter period and much stronger, and during a hurricane can reach heights of 20 m and wave lengths of 400 m. Their effect becomes small at depths of about one-half wavelength, or about 200 m. Thus, even large surface waves primarily affect the power plant itself and the upper part of the CWP. Wave motions induce pressure, drag, lift, inertia, and diffraction forces on the vertical pipe, all of which can be adequately analyzed by existing methods. As outlined by Hove, et al (1978)[8], drag and inertia forces are predicted satisfactorily by the Morison equation with experimental coefficients, and data exists for the maximum oscillating lift force. The CWP is large enough that diffraction effects will be significant, and these are also predicted by existing theory (MacCamy and Fuchs, 1954)[15].

Design critical loads are likely to occur for a combination of waves and currents, although data are lacking for such superimposed interactions. The limited data that does exist suggest that this interaction could alter both the loading patterns and the wave spectra (Tung and Wang, 1973)[16] as indicated in Figure 4.5. The enhanced forces expected from this summation will of course aggravate the second high-priority problem of estimating flexible structure interactions.

4.2.4 Power Plant Induced Loads

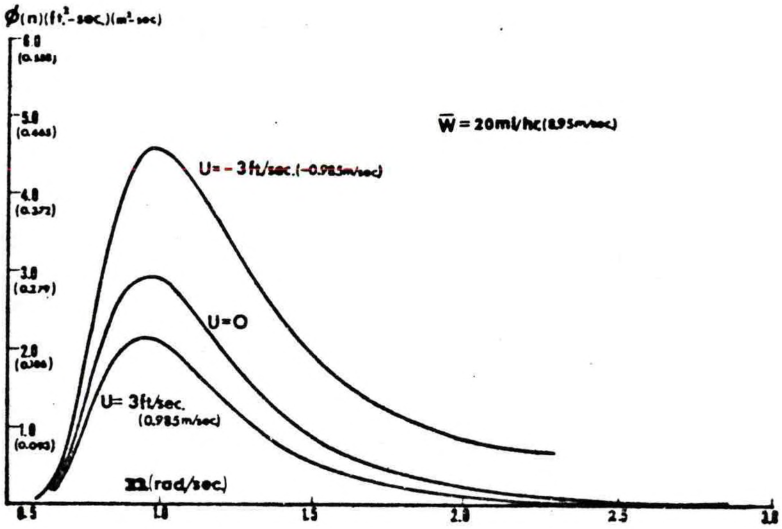
The internal flow in the CWP is a possible contributor to further hydrodynamic loads. Pressure differences due to viscous losses and inlet contraction can couple with the external flow-induced pressure distribution to cause buckling of the pipe wall. Flow deviations in normal plant operations can induce water hammer longitudinal waves through the pipe fluid. Even under normal internal flow, turbulent wall pressure fluctuations can induce travelling bulge waves if the pipe wall is sufficiently flexible. In addition, surface waves can induce strong heave motions in the plant platform, thereby deflecting the pipe significantly. Although these internal flow effects are probably of secondary importance, they should be considered as contributing to the overall induced loads.

4.3 CONCLUSIONS

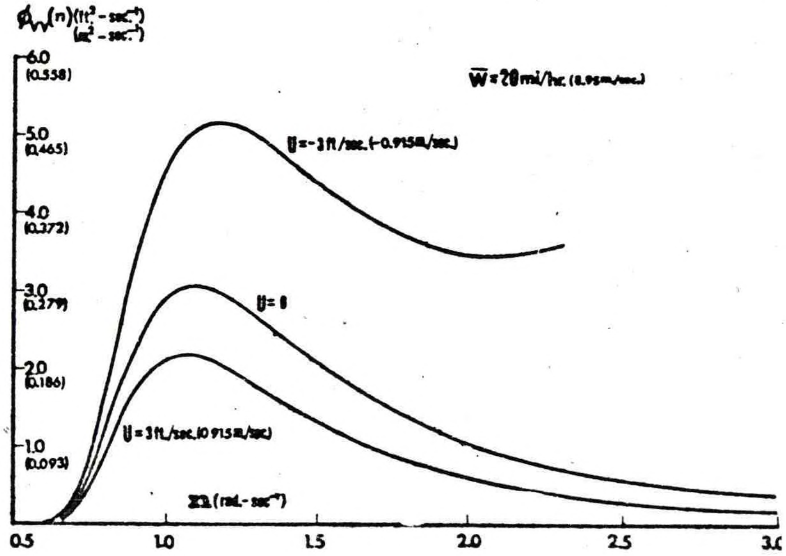
After a careful weighing of the available data and predictive techniques developed to estimate hydrodynamic loads for the CWP analysis, the following conclusions have been reached.

1. At the present time sufficient data exist to define the hydrodynamic loads for a preliminary OTEC cold water pipe design with the assumption that the CWP can be treated as a rigid structure.

2. Since the literature shows that superstructures can have marked effects on fluid-structure interaction, the CWP design should be analyzed as a component of the total plant configuration.



Surface Wave Frequency Spectrum



Velocity Frequency Spectrum

FIGURE 4.5. INFLUENCE OF MEAN FLOW VELOCITIES ON WAVE SPECTRA (Tung and Wang, 1973)[16]

3. In order to assure that the CWP is designed to meet the expected wide array of possible environmental conditions, a series of conservative hydrodynamic loading scenarios should be developed to account for the magnitude as well as frequency composition of the key forcing mechanisms. It is to be noted that, while linear super-position probably adequately addresses the magnitude of the forces, it is usually a poor representation of the important spectra of the loads.

4. It would appear that additional effort to define hydrodynamic loads for flexible structures may be wasteful until the selection of material and plant design configuration are made. If during this selection process such a structure is indicated a detailed engineering investigation employing both experimental and analytical/numerical procedures should be performed to supplement the design.

5. Detailed consideration should be given to the problem of developing preprocessors to prepare the hydrodynamic load data in appropriate form for input to the shell models. This will require a decision as to whether spectral or time dependent solutions of the shell finite element models are to be employed.

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APPENDIX A
DETAILED ATTRIBUTES OF SURVEYED PROGRAMS

GENERAL PURPOSE PROGRAMS

Properties

Program	Shell Wall Construction			Material Properties				Type of Damping			Mass Matrix	
	Layered	Sandwich	Composite	Anisotropic	Nonlinear Elastic	Elastic Plastic	Strain Hardening	Viscous	Structural	Nonlinear	Diagonal	Non-diagonal
ADINA				x	-	x	x	x	-	-	x	x
ANSYS	x	x	-	x	-	x	x	x	x	-	-	x
ASAS	-	x	-	x	x	x	x	x	x	-	x	x
ASEF	x	x	-	x	-	-	-	x	x	-	-	x
ASKA	-	-	-	x	-	-	-	x	-	-	x	x
DYNAL	-	-	-	x	-	-	-	x	-	-	x	x
MARC	x	x		x	x	x	x	x		x	x	x
MARTSAM	-	-	-	x	-	-	-	x	x	-	x	x
MINIELAS	-	-	x	x	-	-	-	x	-	-	x	x
NASTRAN-COSMIC	-	x	-	x	-	-	-	x	x	-	x	x
NASTRAN-MSC	-	x	-	x	-	-	-	x	x	-	x	x
NEPSAP	x	x	x	x	-	x	x				x	x
NISA	x	x	-	x	-	-	-	x	-	-	x	x
PAFEC 70	x	-	-	x	-	-	-	-	-	-	x	x
SAMIS	x	x	-	x	-	-	-	x	x	-	x	x
SAP IV	x	x	-	x	-	-	-	x	-	-	x	-
SESAM 69C	x	-	-	x	-	x	x	x	-	-	x	x
STARDYNE	x	x	-	x	-	-	-	x	-	-	x	-
STRUDL II	-	-	-	x	-	-	-	x	-	-	x	x

GENERAL PURPOSE PROGRAMS

FINITE ELEMENT LIBRARY

Program	Rod	Beam	Curved Beam	Faceted Shell	Curved Shell	Thick Shell	Membrane	Plate	Thick Plate
ADINA	x	x	-	-	x	-	x	-	-
ANSYS	x	x	x	x	-	x	x	x	x
ASAS	x	x	x	x	-	-	x	x	x
ASEF	x	x	x	x	x	x	x	x	x
ASKA	x	x	x	x	x	x	x	x	x
DYNAL(STRUDL)	x	x	-	-	-	-	x	x	-
MARC	x	x	x	-	x	x	x	x	x
MARTSAM	x	x	-	x	-	-	x	x	-
MINIELAS	x	x	-	-	x	x	x	x	x
NASTRAN-COSMIC	x	x	x	x	-	x	x	x	x
NASTRAN-MSC	x	x	x	x	-	-	x	x	-
NISA	x	x	-	-	x	x	x	x	x
NEPSAP	x	x	x	x	-	x	-	x	-
PAFEC 70	x	x	x	x	x	x	x	x	x
SAMIS	x	x	x	x	-	-	x	x	x
SAP IV	x	x	x	x	x	x	x	x	x
SESAM-69C	x	x	x	x	-	x	x	x	-
STARDYNE	x	x	x	x	-	-	x	x	-
STRUDL II	x	x	-	-	-	-	x	x	-

GENERAL PURPOSE PROGRAMS

Loading & Boundary Conditions

	Load Variation					Type of Load					Constraints	
Program	General Spatial	General Transient	Proportional	Different Time History	Random	Point Loads	Surface Tractions	Normal Pressure	Body Force Dead-Weight	Known Movement	General Linear	General Nonlinear
ADINA	x	x	x	x	–	x	x	x		x		
ANSYS	x	x	x	x	x	x	x	x	x	x	x	x
ASAS	x	x	x	x	x	x	x	x	x	x	x	–
ASEF	x	x	x	–	–	x	x	x	x	x	x	–
ASKA	x	x	x	–	x	x	x	x	x	x	–	–
DYNAL (STRUDL)	x	x	–	–	–	x	x	x	–	–	–	–
MARC	x	x	x	x	x	x	x	x	x	x	x	x
MARTSAM	x	x	x	x	–	x	x	x	–	x	x	–
MINIELAS	x	–	x	–	x	x	–	x	x	x	x	–
NASTRAN-COSMIC	x	x	x	–	x	x	x	x	x	x	x	–
NASTRAN-MSC	x	x	x	–	x	x	x	x	x	x	x	–
NISA	x	x			x	x	x	x	x	x	x	–
NEPSAP	x	x				x	x	x			x	
PAFEC 70	x	–	–	–	–	x	x	x	x	x	x	–
SAMIS	–	x	–	x	–	x	x	x	x	x	x	–
SAP IV	–	x	–	x	–	x	x	x	x	x	x	–
SESAM-69C	x	x	–	–	–	x	x	x	x	x	x	–
STARDYNE	–	x	x	x	x	x	x	x	x	x	–	–
STRUDL II	x	x	–	–	–	x	x	x	–	–	–	–

GENERAL PURPOSE PROGRAMS

Solution Procedures

Program	Equation Solver				Eigen-Values		Time Integr.			Condensation	
	Matrix Partitioning	Bandwidth	Skyline	Wave Front	Direct	Iterative	Implicit	Explicit	Equil. Check or Energy Balance	Stiffness	Mass, Damping
ADINA	-	-	x	-		x	x	x	x		
ANSYS	-	-	-	x	x	-	x	-	-	x	x
ASAS	x	-	-	x	x	-	x	-	x	-	-
ASEF	-	-	-	x	-	x	x	-	-	-	-
ASKA	x		-	-	x	-	-	-	-	x	x
DYNAL	-	-	-	x	x	x			-	x	x
MARC	-	-	x	x	-	x	x	x	x	-	-
MARTSAM	x	x	-	-	x	x	-	x	-	x	x
MINIELAS	-	x	-	-	-	x			-	-	-
NASTRAN-COSMIC	-	x	-	x	x	x	x	-	-	x	x
NASTRAN-MSC	-	x	-	x	x	x	x	-	-	x	x
NEPSAP	-	-	-	x	x	x	x	-	x	x	x
NISA	-	-	x	-	x	x	x	-	-	x	x
PAFEC 70	x	x		x	x	x			-	-	-
SAMIS	x	-	-	x	-	x	x	-	-	x	
SAP IV	-	-	x	-	-	x	x	-	-		
SESAM 69C	x	x	-	-					-		
STARDYNE	-	x	x	x	x	x	x	-	-	x	-
STRUDL II	-	-	-	x	-	x	x	-	-	x	x

GENERAL PURPOSE PROGRAMS

Other Attributes & Information

Program	Automatic Mesh Generation	Automatic Load Generation	Automatic Node Renumbering	Plotting	Restart	Added Mass	Large Strains	Entirely In-Core	Minimum Core Required	Computer
ADINA	x	x		-	x	-	x	-		ICU
ANSYS	x	x	x	x	x	-	-	-	50K	ICU
ASAS	x	-	-	x	x	-	x	-	32K	ICU
ASEF	-	-	-	x	x	-	-	-		IC
ASKA	x			-	x	-	-	-	32K	ICU
DYNAL	x	-	x	-	x	-	-	-		IU
MARC	x	x	x	x	x	-	x	-	60K	ICU
MARTSAM	-	-	x	x	x	-	-	-	65K	U
MINIELAS	-	-	x	-	-	-	-	x	32K	I
NASTRAN-COSMIC	-	-	x	x	x	-	-	-	50K	ICU
NASTRAN-MSC	-	-	x	x	x	-	-	-	50K	ICU
NEPSAP	x	x	-	x	x	-	-	-	40K	ICU
NISA	x	x	-	x	x	-	x	-	40K	CU
PAFEC 70	x	x	x	x	-	-	-	x	10K	U
SAMIS	-	x	-	x	x	-	-	-		CU
SAP IV	x	x	-	-	x	-	-	-	48K	ICU
SESAM 69C	x	x	x	x	x	-	-	-	40K	ICU
STARDYNE	x	x	x	x	x	-	-	-	32K	C
STRUDL II	x	-	x	-	x	-	-	-		IU

I: IBM
C: Control Data
U: Univac

SPECIAL PURPOSE PROGRAMS
FOR DYNAMIC RESPONSE OF SHELL STRUCTURES

Program	Type	Analysis Type				Nonlinear		Proprietary	Service Bureau Use
		Response Spectrum	Random	Time Hist. Modal	Time Hist. Direct	Geometric	Material		
DYNAPLAS	FE	-	-	-	x	x	x	-	-
KSHEL	FI	-	-	x	-	-	-	-	x
PETROS 3	FD	-	-	-	x	x	x	L	-
REPSIL	FD	-	-	-	x	-	x	-	-
SABOR/DRASTIC	FE	-	-	-	x	x	x	-	-
SATANS	FD	-	-	-	x	x	-	-	-
SHORE	FD	-	-	-	x	x	x	-	-
SLADE D	FE	-	-	-	x	-	-	-	-
STAGS B	FDE	-	-	-	x	x	x	-	-
STARS	FI	-	-	-	x	-	x	-	-
TRAINS	FE	-	-	-	x	x	x	-	-
TROCS	FD	-	-	-	x	x	x	-	-
WHAM	FE	-	-	-	x	x	x	x	

FE: Finite Element
FD: Finite Difference
FDE: Finite Difference Energy Method
FI: Forward Integration

L: Limited Distribution
x: Yes
-: No
Blank: Unknown

SPECIAL PURPOSE PROGRAMS

Properties

	Shell Wall Construction			Material Properties						Type of Damping			Mass Matrix	
Program	Layered	Sandwich	Composite	Anisotropic	Nonlinear Elastic	Elastic Plastic	Stain Hard.	Axysimm. Variat. Only	General Variat.	Viscous	Structural	Nonlinear	Diagonal	Non-Diagonal
DYNAPLAS	-	-	-	-	-	x	x	x	-	-	-	-	-	x
KSHEL	x	x	-	x	x	-	-	x	-	x	x	-		
PETROS 3	x	-	-	-	-	x	x	-	x	-	-	-		
REPSIL	-	-	-	x	-	x	x	-	-	-	-	-		
SABOR/DRASTIC	-	-	-	x	x	x	x	x	x	-	x	-	-	x
SATANS	x	x	-	-	-	-	-	x	-	-	-	-		
SHORE	x	-	-	x	-	x	x	-	-	-	-	-		
SLADE D	x	-	-	x	-	-	-	-	x	-	-	-	x	-
STAGS B	x	-	x	x	-	x	x	-	x	x	x	-	x	-
STARS	x	x	x	x	x	x	x	x	-	-	-	-		
TRAINS	-	-	-	-	-	x	x	x	x	-	-	-	-	x
TROCS	x	-	-	x	-	x	x	-	-	x	x	-		
WHAM	-	-	-		x	x	x	-	x	x	x	x	x	-

SPECIAL PURPOSE PROGRAMS

Shell Model/Finite Element Library

Program	Geometry		Finite Difference		Finite Elements					Stiffeners		
	General	Shell of Revolution	1-D Grid	2-D Grid	Rod	Beam	Axisymm. Shell Shell	Shell	Thick Shell	Discrete	Smeared	Fourier Series in Circum Dir.
DYNAPLAS	-	x	-	-	-	-	x	-	-	x	x	x
KSHEL	-	x	-	-	-	-	-	-	-	x	x	x
PETROS 3	x	-	-	x	-	-	-	-	-	-	-	-
REPSIL	x	-	-	x	-	-	-	-	-	-	-	-
SABOR/DRASTIC	-	x	-	-	-	-	x	-	-	x		x
SATANS	-	x	x	-	-	-	-	-	-	-	-	x
SHORE	-	x	-	x	-	-	-	-	-	-	-	
SLADE D	-	x	-	-	x	-	-	x	-	-	-	-
STAGS B	x	-	-	x	x	-	-	-	-	x	x	-
STARS	-	x	x	-	-	-	-	-	-	x		x
TRAINS	x	x	-	-	-	x	x	x	-	x	-	-
TROCS	-	x	-	x	-	-	-	-	-	-	-	-
WHAM	x	x	-	-	-	x	x	x	-	x	-	-

SPECIAL PURPOSE PROGRAMS

Loading & Support Conditions

Program	Load Variation					Type of Load					Supports		
	General Spatial	General Transient	Proportional	Different Time Histories	Random	Point Loads	Surface Tractions	Normal Pressure	Body Force Dead.-Weight	Known Movement	Axisymmetric	General	Boundaries Only
DYNAPLAS	x	x	x	-	-	x	x	x	x	-	x	x	-
KSHEL	x	x	x	-	-	x	x	x	x	-	x	-	x
PETROS 3	x	x	-	-	-	-	-	x	-	-	-	-	x
REPSIL	x	x	-	-	-	-	-	x	-	-	-	-	x
SABOR/DRASTIC	x	x	-	x	-	x	x	x	x	x	-	x	-
SATANS	x	x	x	-	-	-	x	-	-	-	x	x	x
SHORE	x	x	-	x	-	x	x	x	-	-	-	-	x
SLADE D	x	-	x	-	-	-	x	x	-	-	-	-	x
STAGS B	x	x	x	-	-	x	x	x	x	x	x	x	-
STARS	x	x	-	x	-	x	x	x	x	-	-	-	x
TRAINS	x	x	-	x	-	x	x	x	-	x	x	x	x
TROCS	x	x	-	x	-	-	x	x	-	-	-	-	x
WHAM	x	x	x	x	-	x	x	x	-	x	x	x	-

SPECIAL PURPOSE PROGRAMS

Solution Procedures

Program	Equation Solver				Eigen-Values		Time Integr.			Conden-sation	
	Matrix Partitioning	Bandwidth	Skyline	Wave Front	Direct	Interative	Implicit	Explicit	Equil. Check or Energy Balance	Stiffness	Mass, Damping
DYNAPLAS	-	x	-	-	-	-	x	x	-	-	-
KSHEL	-	x	-	-	-	x			x	-	-
PETROS 3					-	-	-	x	x	-	-
REPSIL					-	-	-	x		-	-
SABOR/DRASTIC	-	-	-	x	-	-	x	-		-	-
SATANS	-	x	-	-	-	-	x	-	x	-	-
SHORE					-	-	-	x	-	-	-
SLADE D					-	-	-	x	-	-	-
STAGS B	-	-	x	-	-	x	x	x	x	-	-
STARS					x	-	x	-	x	-	-
TRAINS	x	-	-	-	-	-	x	-	x	-	-
TROCS					-	-	-	x	-	-	-
WHAM	-	-	-	-	x	-	-	x	x	-	-

SPECIAL PURPOSE PROGRAMS

Other Attributes & Information

Program	Automatic Mesh Generation	Automatic Load Generation	Automatic Node Renumbering	Plotting	Restart	Added Mass	Large Strains	Entirely In-Core	Minimum Core Required	Computer
DYNAPLAS	x	x	-	-	x	-	-	-		IC
KSHEL	-	-	-	-	-	-	-	x	33K	ICU
PETROS 3	-	-	-	x	x	-	x	x		I
REPSIL	-	-	-	x	x	-	x	x		
SABOR/ DRASTIC	x	x	-	x	x	-	-	x	45K	IC
SATANS	-	-	-	-	x	-	-	x	36K	IC
SHORE	-	x	-	x	x	-	-	x	62K	CU
SLADE D	-	-	-	-	x	-	-	-		C
STAGS B	x	x		x	-	-	-	-		CU
STARS	-	-	-	x	x	-	-	-		IU
TRAINS	x	x		x	x	x	-	-		C
TROCS	-	-	-	x	-	-	-	-		U
WHAM	-	x	-	x	-	-	x	x		CIU

I: IBM
C: Control Data
U: Univac

APPENDIX B

SOURCES FOR SURVEYED PROGRAMS

GENERAL PURPOSE PROGRAMS

ADINA	Prof. K.J. Bathe, Massachusettes Institute of Technology, Dept. Mechanical Engineering, Cambridge, Mass., 02139
ANSYS	Swanson Analysis Systems, Inc., P.O.Box 65, Houston, Pa., 15342
ASAS	Atkins Research and Development, Ashley Road, Epsom, Surrey, England
ASEF	Lab. Tech. Aerospatiales, Liege, Belfium
ASKA	ASKA-Group, Pfaffenwaldring 27, Stuttgart-80, West Germany
DYNAL(STRUDL)	McDonnell Douglas Automation, Box 516, St. Louis, Mo., 63166
MARC	MARC Analysis Research Corp., 260 Sheridan Ave., Suite 314, Palo Alto, Ca., 94306
MARTSAM	NAVSHIPS, Code PMS 3-2-421
MINIELAS	Dr. S. Utku, Duke University, School of Engineering, Durham, N.C., 27706
NASTRAN-COSMIC	COSMIC, 112 Barrows Hall, University of Georgia, Athens, Georgia, 30601
NASTRAN-MSC	MacNeal-Schwendler Corp., 7422 N. Figuero St., Los Angeles, Ca., 90041
NEPSAP	P. Sharifi, Lockheed Missile and Space Co., Inc., Sunnivale, Ca., 94088
NISA	Engineering Mechanics Research Corp., P.O. Box 695, Troy, Mich., 48099
PAFEC-70	Henshell, Notts University, University Park, Nottingham, England
SAMIS	Prof. R.J. Melosh, Dept. Civil Engineering, Duke University Durham, N.C. 27706
SAP IV	NISEE/Computer Applications, Davis Hall, University of California, Berkeley, Ca., 94720
SESAM 69	Det Norslee Veritas, P.O. Box 6060, Etterstad, Oslo 6, Norway

STARDYNE	Dr. R. Rosen, Mechanics Research, Inc., 9841 Airport Blvd., Los Angeles, Ca., 90045
STRUDL II	ICES Users Group, Inc., P.O. Box 8243, Cranston, R.I., 02920

SPECIAL PURPOSE PROGRAMS

DYNAPLAS	Dr. W.E. Haisler, Dept. Aerospace Engineering, Texas A*M University, College Station, Texas 77843 (COSMIC)
KSHEL	Dr. A. Kalnins, Dept. Mech. Eng. & Mechanics, Lehigh University, Bethlehem, Pa., 18015
PETROS 3	Dr. N.J. Huffington, Jr., U.S. Army Ballistic Research Lab., Aberdeen Proving Ground, Md., 21005
REPSIL	See PETROS 3
SABOR/DRASTIC	Dr. S. Klein, Ohio Ford Corp., Ford Road, Newport Beach, Ca., 92663
SATANS	R.E. Ball, Code 57Bp, Naval Postgraduate School, Monterey, Ca., 93940 (COSMIC)
SHORE	P. Underwood, Lockheed Missile and Space Co., 3251 Hanover St., Palo Alto, Ca., 94304
SLADE D	Dr. S.W. Key, Sandia Laboratories Division 1541, Albuquerque, N.Mex., 87115
STAGS	Dr. B. Almroth, Lockheed Missile and Space Co., 3251 Hanover St., Palo Alto, Ca., 94304
STARS	V. Svalbonas, The Franklin Instittue, Philadelphia, Pa., 19103
TRAINS	R.F. Jones or J.E. Roderick, DTNSRDC Structures Dept., Bethesda, Maryland 20084
TROCS	See SHORE
WHAM	Prof. T. Belytschleo, Dept. of Materials Engineering, University of Illinois, Chicago Circle, Ill., 60680

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