NOAA Technical Report OOE5

OTEC Cold Water Pipe: Program, Problems, and Procedures

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OTEC COLD WATER PIPE: PROGRAM, PROBLEMS, AND PROCEDURES

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ABSTRACT. The purpose of this presentation is to provide a comprehensive overview of the OTEC Cold Water Pipe program. The overview will include a discussion of the technical problems being addressed, the rationale behind the technology development program, and the analytical procedures used to define pipe behavior. Emphasis will be placed on demonstrating what planning has occurred in the program plan. Anticipated outputs and application to other marine technologies will also be projected. A detailed discussion shall be presented on the analytical models developed to define the dynamics of the cold water pipe. Analytical results shall be compared to model test and at-sea test data to indicate the validity of the design tools in predicting pipe motions and stresses.

I. Introduction

The Ocean Thermal Energy Conversion (OTEC) Program involves many new and interesting problems. The cold water pipe (CWP) subsystem includes several of the most difficult problems in the OTEC system. The reasons are quite simple: The CWP is immense in size, subject to tremendous loads, and will be difficult to construct and deploy safely.

To develop a CWP that can withstand the OTEC environment and survive, reasonable pipe designs must be formulated. To aid in the development of such CWP designs, the Government has prepared a program leading to the design and development of several viable alternative CWP concepts.

In this paper the OTEC CWP program development and format will be explained and the analytical tools used to design the CWP shall be indicated and their predictions compared to empirical data. Program outputs will be postulated, and their relevancy to other marine programs projected.

II. Program Development

Background

The OTEC CWP program has been formulated around two major objectives:

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- To advance the technologies fundamental to design, construction, deployment, and operation of a low technical risk CWP for the OTEC pilot plant

- To assemble and maintain a technical information data base of the OTEC pilot plant CWP to ensure

  - Design verification and selection,
  - Design competitiveness.

The CWP program is one of several similar programs in the OTEC system that are geared to support the Government's plan to have a competitive procurement on the design, development, and operation of an OTEC pilot modular experiment, is tentatively slated to provide power in the range of 10 to 40 Megawatts of electrical energy (MWe).

The OTEC 10/40 MWe pilot plant's proposed CWP would be the longest, moveable, flexible structure in the world with dimensions of 1,000 meters in length and 9 meters in inside diameter. The 9-meter diameter-sized OTEC CWP is planned for deployment in 1983-84. A 30 meter diameter pipe is planned for larger (100/400 MWe) OTEC plants in the late 1980's.

Program Outline

As in any technical program there are several general steps involved in its management, namely:

- Problem Definition/State of the Art Assessment

- Program Development and Planning

- Program Execution

- Evaluation of Program Results

- Technology Transfer of Key Results.

In this section of the paper, the first two program steps will be discussed. In addition, a brief summary will be given of the current program elements to indicate what is being executed. Technology transfer will be the topic of the last section of the paper.

Problem Definition/State-of-the-Art Assessment

The OTEC CWP program has been planned to address and resolve the major technical issues of the CWP. Although some problems can never be resolved until actual prototype operations have begun, nevertheless there are several problems that can be addressed prior to the development and deployment of the CWP. The Major CWP problems that have been identified to data are arranged in a priority list as follows:

- Hydrodynamic load definition

- o Deployment/recovery/survival techniques
- o Platform attachments and pipe joints
- o Structural analysis of CWP behavior
- o Integration into other OTEC subsystems
- o Special material/component characteristics
- o Constructability
- o Operation and maintainability.

A more complete breakdown of the elements involved in each problem area can be found in reference 1.

To address the pipe problems, several different schemes were employed. Surveys of the current state of knowledge and technology in related disciplines were conducted. Work efforts were then started at modifying existing theory or practices to be applied to the OTEC CWP problems. Conceptual designs of CWPs were developed to determine the critical unknowns. Comparative analyses of conceptual designs and the preparation of preliminary pipe designs enabled designers to focus on several pipe configurations after determining the range of pipe behavior that was deemed acceptable.

In addition a series of laboratory and at-sea model tests have supplied further empirical data on the validity of design tools and pipe concepts.

To illustrate the time sequence of the CWP program phases, figure 1 is presented. The present program is concentrating on the development of several preliminary pipe designs as indicated in figure 1.

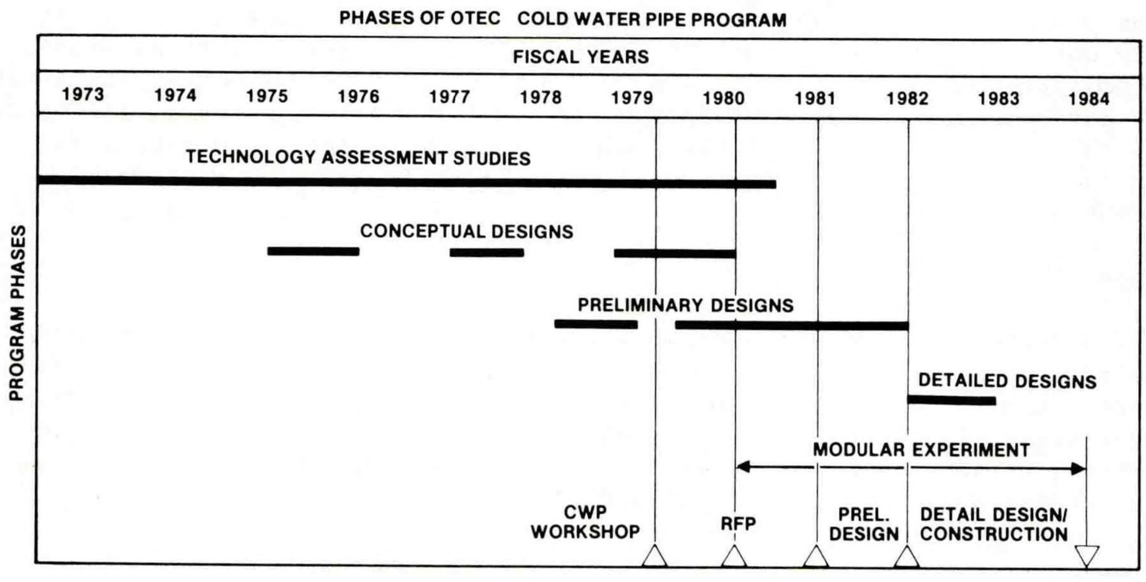

Figure 1.--Phases of OTEC cold water pipe program.

Program Development and Planning

Once the problems have been defined and the current technology assessed, the program elements, schedules, and budgets are formulated. The program was defined by three elements:

- Analysis - consists of specific technology assessments, design work, analytical tool development
- Model Tests - comprises the small-scale laboratory testing of fluid, structure, and material problem areas
- Verification - includes at sea test efforts and tests nearly full-scale scale models or tests of pipe configurations/materials similar to those of proposed CWP designs.

A fourth element, integration, completed the program. The element of integration was included in the program. To assure that the three program element outputs were compatible with program objectives and could be used to solve pipe problems.

The final output of the integration effort, and that of the CWP program, could be defined as being a design manual. The manual would be used to fulfill the program objectives. The manual would be the repository of the technical data base of CWP knowledge and could be used to supply necessary information to assure design competitiveness and data to assure adequate evaluation of proposed CWP designs for the OTEC pilot plant.

To demonstrate how the program was developed, figure 2 is presented. The relationship between FY 79/80 program elements, CWP problems or program unknowns, as listed in the previous section, and the program phases is demonstrated in figure 2. The figure is meant to be illustrative of the organization of the CWP program. That is, there are often work efforts in three program elements all directed to solving certain program areas. Also it is noted from figure 2 that it is possible to conduct analytical studies of such problems as construction or deployment prior to any actual construction work has been started on a prototype CWP. A final point indicated in figure 2 is that the development of the design manual is iterative in nature and that the data in the manual are constantly being improved as more problem areas are addressed.

Present Program Elements

The current program is concentrating on several items. The most important problem is the validation of the analytical models used as CWP design tools. Several efforts are directed to this problem. A computer code developed by Hydronautics, Inc.[2], known as the NOAA/DOE* CWP Analytical Model is being exercised on several preliminary CWP designs. Improvements in the code and in a similar design tool known as ROTEC[3] are continuing.

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*NOAA/DOE is an abbreviation of National Oceanic and Atmospheric Administration and Department of Energy, the sponsors of the Hydronautics work.

OTEC COLD WATER PIPE PROGRAM WORK FLOW

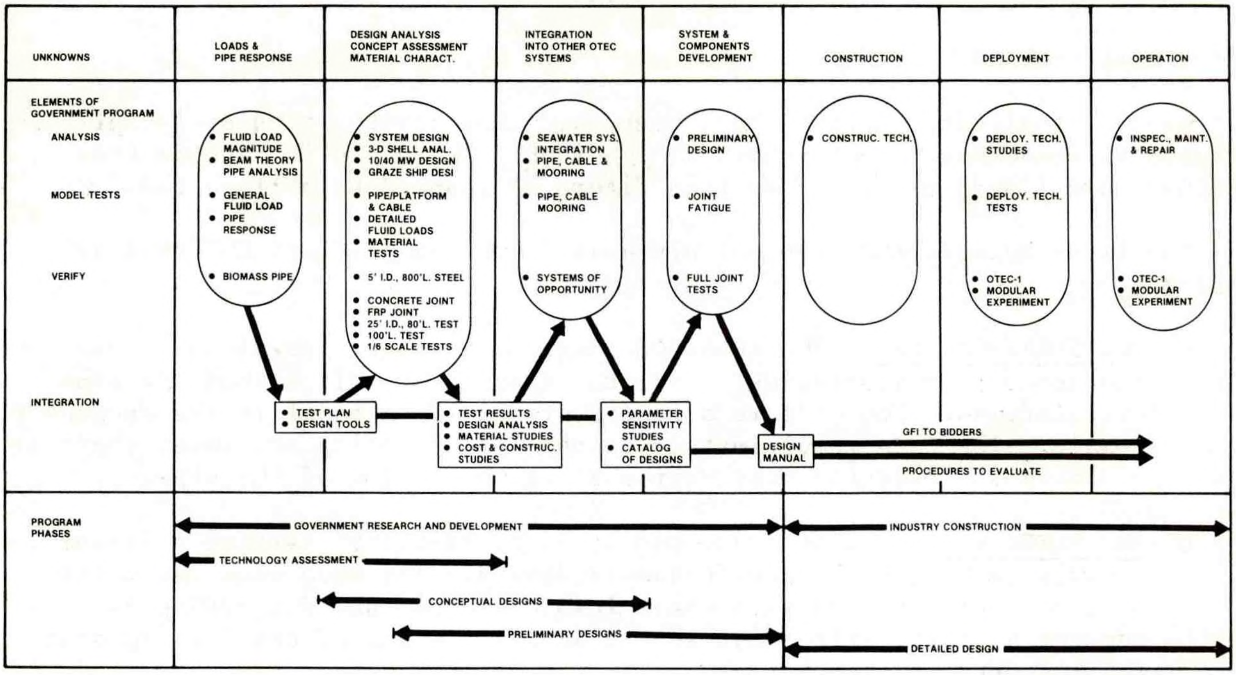

Figure 2.--OTEC cold water pipe program work flow.

In addition, model test programs have begun to supply empirical data necessary in the design tool validation. Model basin tests are being conducted on a 1/30th scale model of the X-1** platform CWP system[4] that suffered a pipe failure earlier this year near Catalina Island Calif. Another test program is planned on various scale model OTEC Platform/CWP systems both in the laboratory and at sea. Specific model tests are also being conducted addressing such areas as vortex shedding in shear flow and vortex suppression devices.

Plans are being formulated for an at-sea test of a sufficient magnitude (approximately 1/6th scale of the 9-meter-diameter CWP) to provide data on CWP structural response. It is anticipated that the at-sea test data can be used both to validate design tools and to extrapolate the behavior of prototype CWPs for the OTEC pilot plant.

Since the major problem being addressed in the CWP program is validation of analytical tools a brief discussion is warranted of the various analytical models and the work to date in validating the models.

**X-1 is the name of a semisubmersible owned by Deep Oil Technology Co., used as the platform of a recent at-sea test of a 5-foot-diameter steel pipe, 500 feet long.

Model Descriptions

Several analytical methods have been used to study the coupled CWP/plaform structural responses to environmental loadings. The analytic methods treat the CWP as a linear elastic beam (see figure 3) coupled to a rigid platform.

The three methods most extensively used in the analysis of CWP designs include:

- o The NOAA/DOE Code. The NOAA/DOE code, as mentioned previously, was developed by Hydronautics[2] using the transfer matrix method for pipe calculations. The code is a linear elastic beam model in the frequency domain. The code is ultimately capable of accepting any input loads as a continuous function that varies along the length of the pipe.
- o The ROTEC Code. ROTEC developed by J. R. Paulling[3] is also a linear elastic beam model in the frequency domain. The code uses the method of finite element solution where loading is defined for each pipe segment at a specific point as the averaged value of the loading over the segment length.
- o The HULPIPE Code. TRW has developed a nonlinear elastic beam model of the CWP in the time domain. The code utilizes the technique of finite differences in its solutions[5].

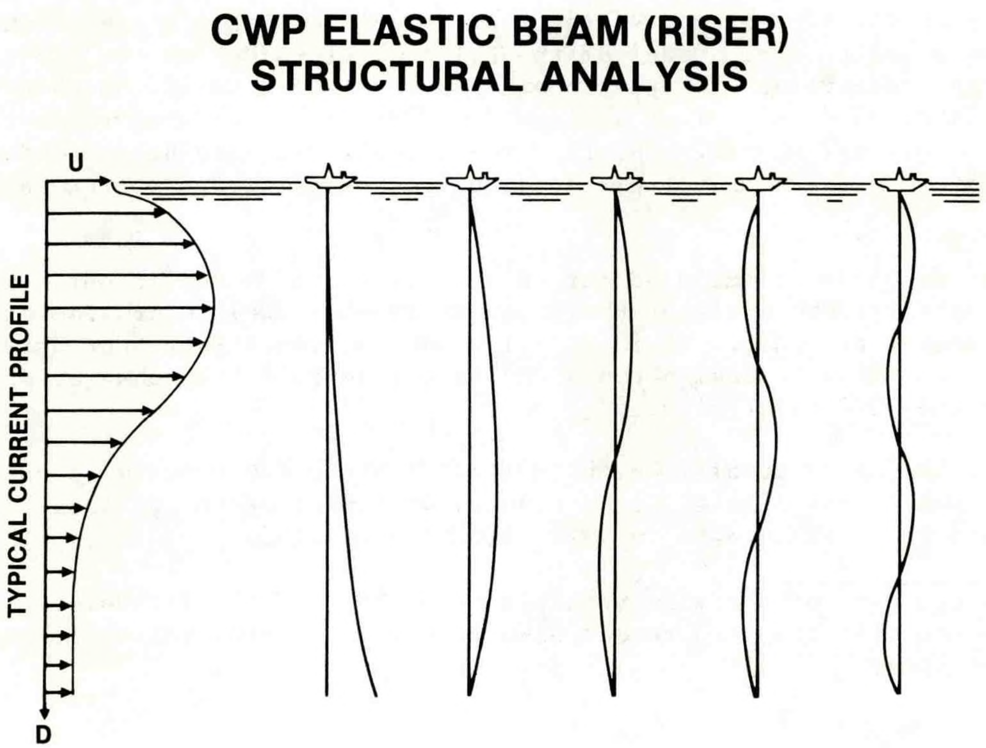

Figure 3.--Structural analysis of cold water pipe (elastic beam).

There have been several other frequency and time domain codes developed, but none have been used as extensively in the analysis of CWP designs as the above three codes. (For a comparative analysis of prior OTEC CWP analytical codes see reference 6.)

Comparison of Models

In References 7 and 8 an assessment has been made of the similarities and differences between the above three cited CWP analytical codes. The comparisons between codes were made by comparing analytical outputs to sample test cases of conceptual CWP designs. Additional comparisons have been made between analytical predictions and actual empirical data from laboratory model test basin efforts and at-sea test conditions. The NOAA/DOE code has been compared to model basin tests. The ROTEC code has been compared to some at-sea test data and will be compared to a series of model basin tests of the X-1 platform/CWP tests[4].

Generally speaking all three methods are capable of treating a variety of rigid and articulated CWPs attached to various OTEC platforms in both wave and current fields. Table 1 taken from reference 8 summarizes the capabilities of the three analytical methods.

Table 1.--Comparison of capabilities of theoretical CWP analysis methods

Feature/Capability	NOAA/DOE	ROTEC	HULPIPE
Loadings			
Non-Linear	No	No	Yes
Uni-Directional Waves	Yes	Yes	Yes
Directional Waves	Yes	IP	Yes
Steady Current	Yes	IP	Yes
Vortex Shedding	Yes	No	Yes
Arbitrary Loads	Yes	No	Yes
Internal Flow	Yes	No	Yes
CWP Geometry			
Joints	Yes	Yes	Yes
Non-Linear Damping	AP	AP	Yes
Wave/Current Interaction	No	IP	Yes
Moorings, etc.	Yes	No	No
Platform			
Frequency Dependence	Yes	Yes	No
Full CWP Coupling	Yes	Yes	Yes

Where — IP denotes in progress

AP denotes approximate treatment

Another way of comparing the three codes is by the analysis of theoretical results for a sample test problem. In figure 4 (ref. 5) a generally good agreement is noted amongst the three CWP codes. However, when a current field is introduced into the sample test problem the comparison is not as good (ref. 5). This and other cases of discrepancies between analytical model codes for sample test cases have been discussed in detail in reference 8. Further work is planned for a thorough validation of the models and will be the focus of attention in the FY 80 CWP program.

Comparisons between laboratory data and theoretical predictions have been conducted in references 2 and 9 for the OTEC-1 and the OTEC 100 MWe spar model tests as shown in figures 5 and 6, respectively. Predicted and measured platform motions are in good agreement. CWP bending moments predicted and measured are also in good agreement as seen in figures 5 and 6.

The above comparisons are for a CWP modeled as an elastic beam. However, the CWPs now under study have thickness-to-diameter ratios and cross-sectional stiffnesses small enough to characterize the pipes as acting as a thin-shell, membrane structure. This is especially true for CWPs being designed out of elastomers and polyethylene. As illustrated in figure 7, the environmental loading on the pipe due to currents and waves and vortex shedding is three dimensional and unsteady. It is quite possible to excite the shell-like

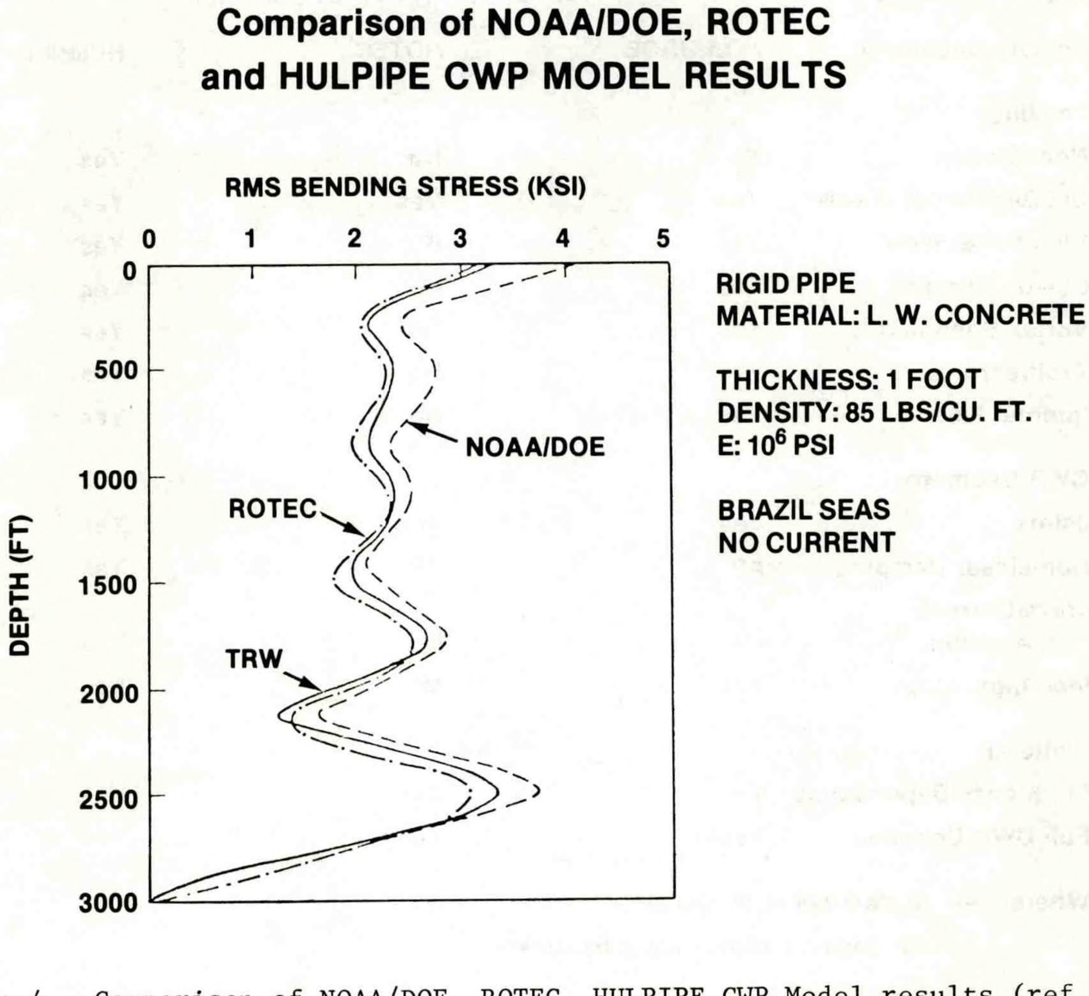

Figure 4.--Comparison of NOAA/DOE, ROTEC, HULPIPE CWP Model results (ref. 5).

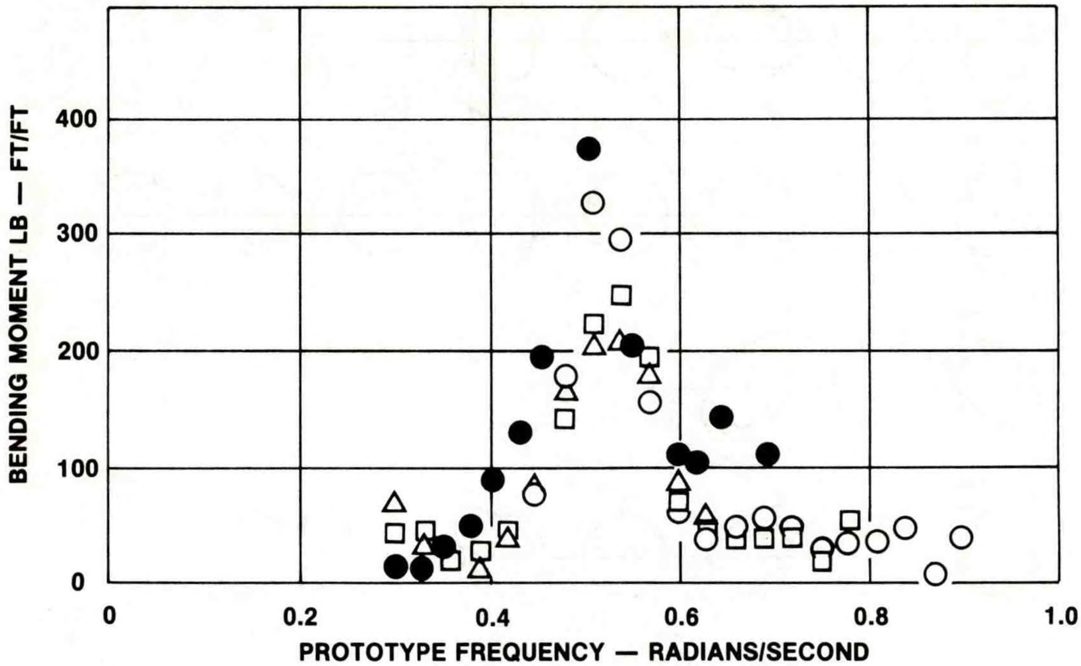

Figure 5.--Comparison of measured and predicted bending moments for stiff OTEC-1 CWP with rigid attachment (ref. 2).

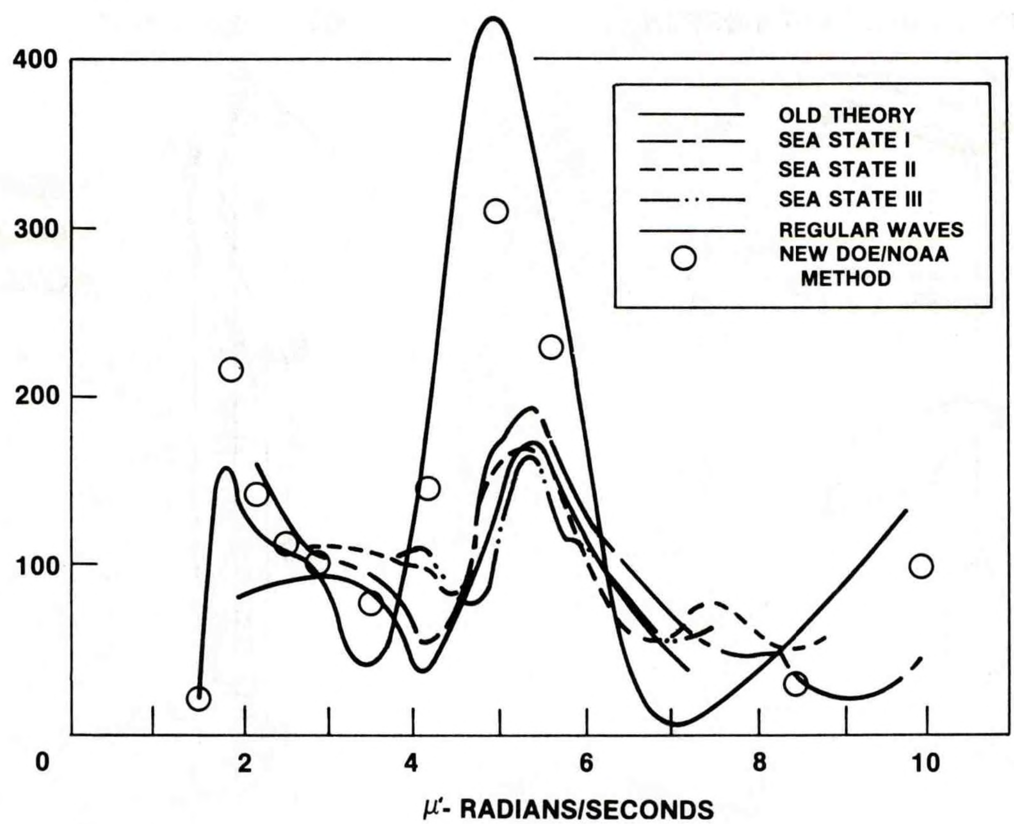

Figure 6.--Comparison of measured and predicted bending moment #2 for CWP rigidly attached to 400 MWe Spar (ref. 9).

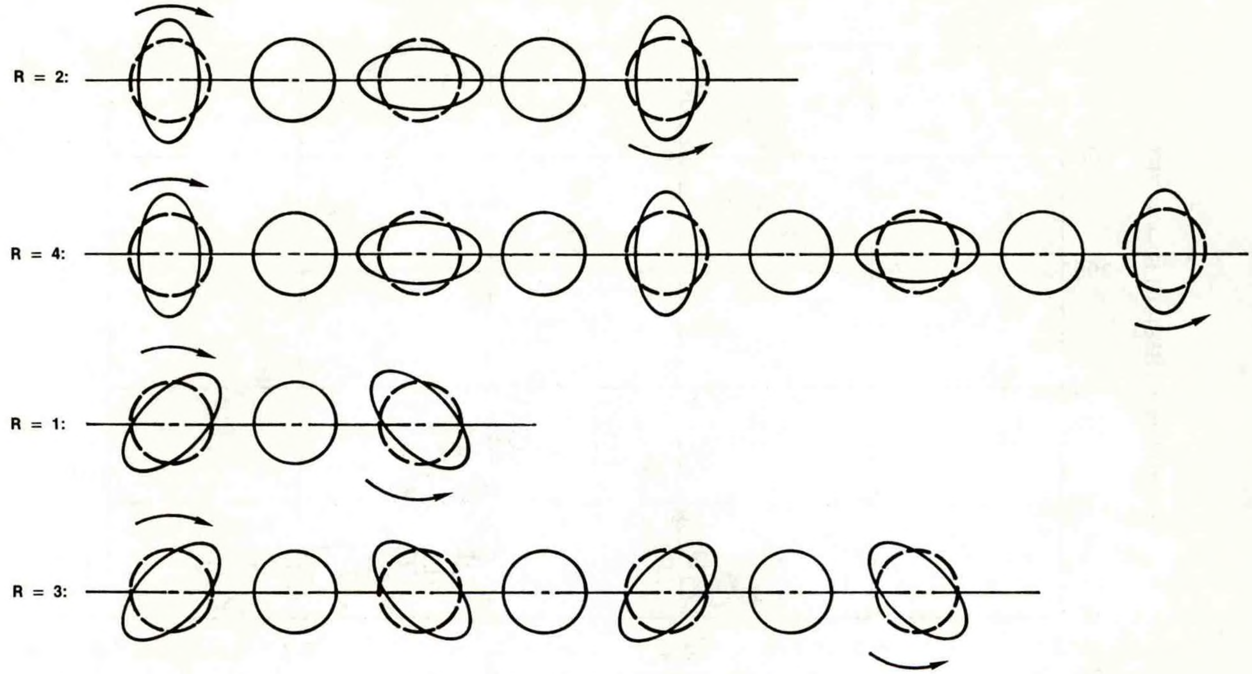

Figure 7.--Response of CWP to complex current profile.

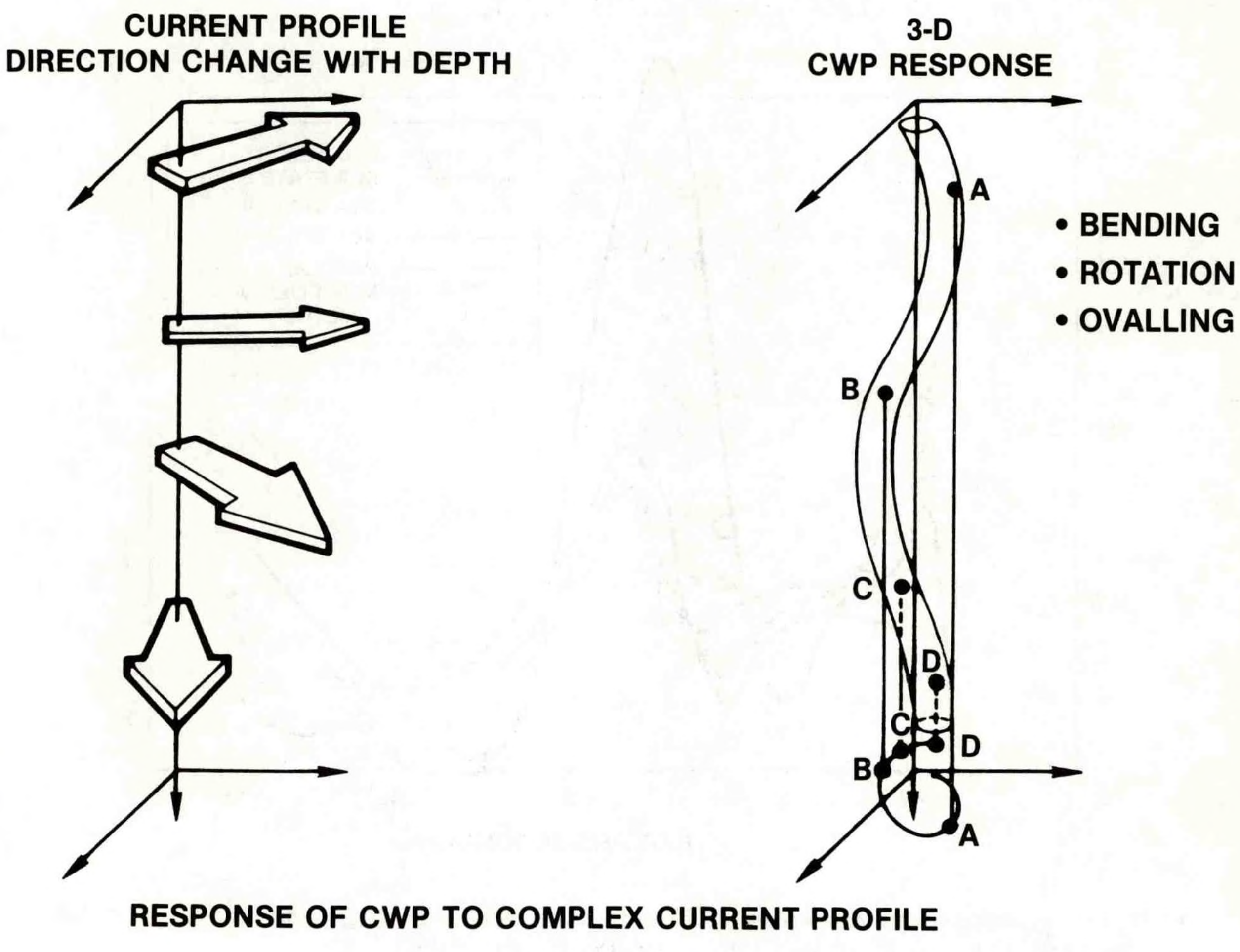

Figure 8.--Ovalling Excitation Modes (ref. 10).

circumferential modes of oscillation that are illustrated in figure 8. Resonance at any shell modes could prove fatal to the pipe either catastrophically or from a corrosion fatigue viewpoint.

Currently underway is a work effort to develop analytical models of the three-dimensional, nonlinear structural response of OTEC CWPs to environmental loading. It is expected that the analysis will be conducted mostly in the time domain to retain the phase information between loads and displacements. The shell analysis should substantially increase the capability of designers to predict the pipe responses to complex environmental loads across complex pipe geometries.

IV. Program Outputs

The outputs of the OTEC CWP program can be summarized as follows. The program has captured the attention of a wide variety of marine experts and has brought to the forefront some new advances in our basic understanding of several marine technological and engineering problems. Researchers from the oil industry, aerospace companies, naval architecture firms, and academic and government laboratories are all participating in the program.

The following specific technology has been developed:

- Structural Analysis of Large Ocean Structures. The NOAA/DOE, ROTEC, and HULPIPE codes along with several other related marine riser and drill string codes have been improved and expanded in capabilities because of the work efforts in the OTEC CWP program.

- Definition of the Hydrodynamic and Environmental Loading of Large Ocean Structures. Not discussed in any detail in this paper but a large part of the CWP program, the work efforts related to fluid forces on offshore structures has substantially advanced the understanding of such loads. There have been several basic and applied studies on such topics as high Reynolds number flows, vortex shedding, vortex correlation length, shear flow, effects of roughness on drag, and lift coefficients. All the studies are applicable to several ocean structure problems.

- Computer Applications to Ocean Systems. The complexity of the CWP analytical model codes has pushed the novel use of new, sophisticated computer computational techniques to ocean systems. The work on CWP model codes is directly related to other computer-based marine analysis tools.

- Development of Large Ocean Structures. Through the various design efforts and studies of construction, deployment, maintenance and repair problems involved in the OTEC CWP, a better understanding of development issues for large ocean structures has been gained.

In summary, the work efforts involved in the OTEC cold water pipe program have lead to a clearer understanding of the many complex interdisciplinary problems associated with the pipe. The technology developed in the CWP program is directly related to other marine programs in such areas as deep ocean dumping, marine mineral extraction, pipeline laying, deep sea drilling, and deployment of many large ocean structures.

The OTEC CWP program can be considered as a focal point for ocean engineering and an example of the way to approach other similar problems in the future.

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