AD 786 487

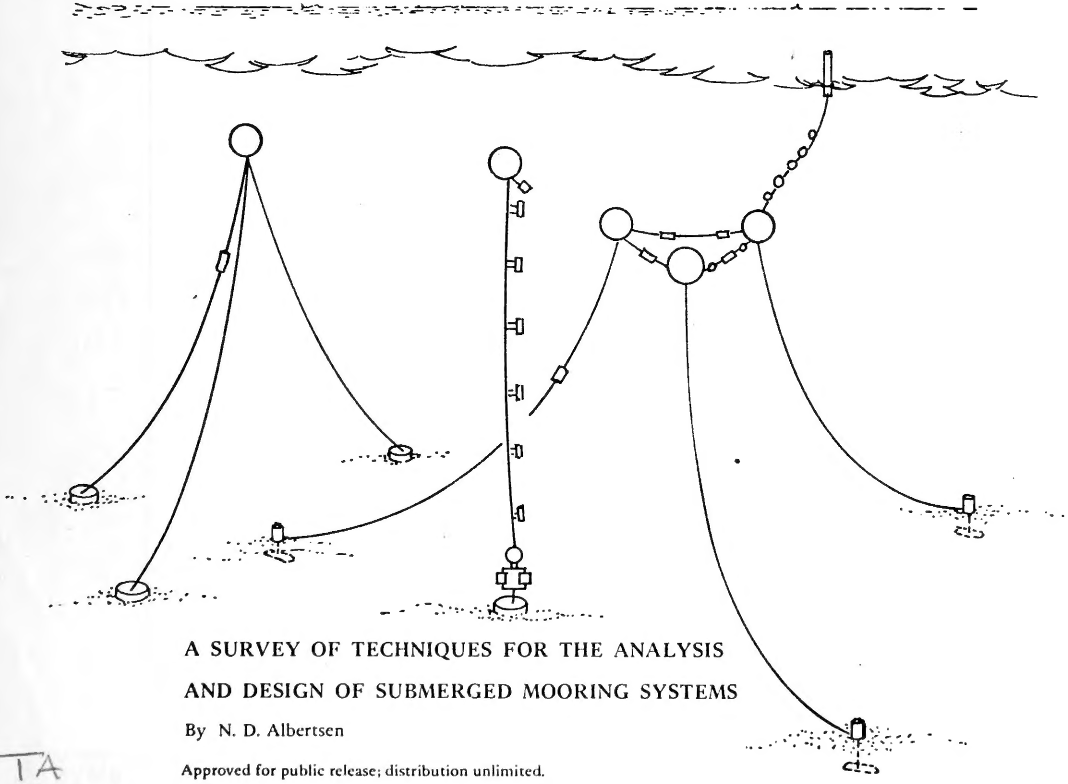
2

509

Technical Report
R 815

Sponsored by
NAVAL FACILITIES ENGINEERING COMMAND
August 1974

CIVIL ENGINEERING LABORATORY
NAVAL CONSTRUCTION BATTALION CENTER
Port Hueneme, CA 93043



A SURVEY OF TECHNIQUES FOR THE ANALYSIS AND DESIGN OF SUBMERGED MOORING SYSTEMS

By N. D. Albertsen

Approved for public release; distribution unlimited.

2

509

Technical Report

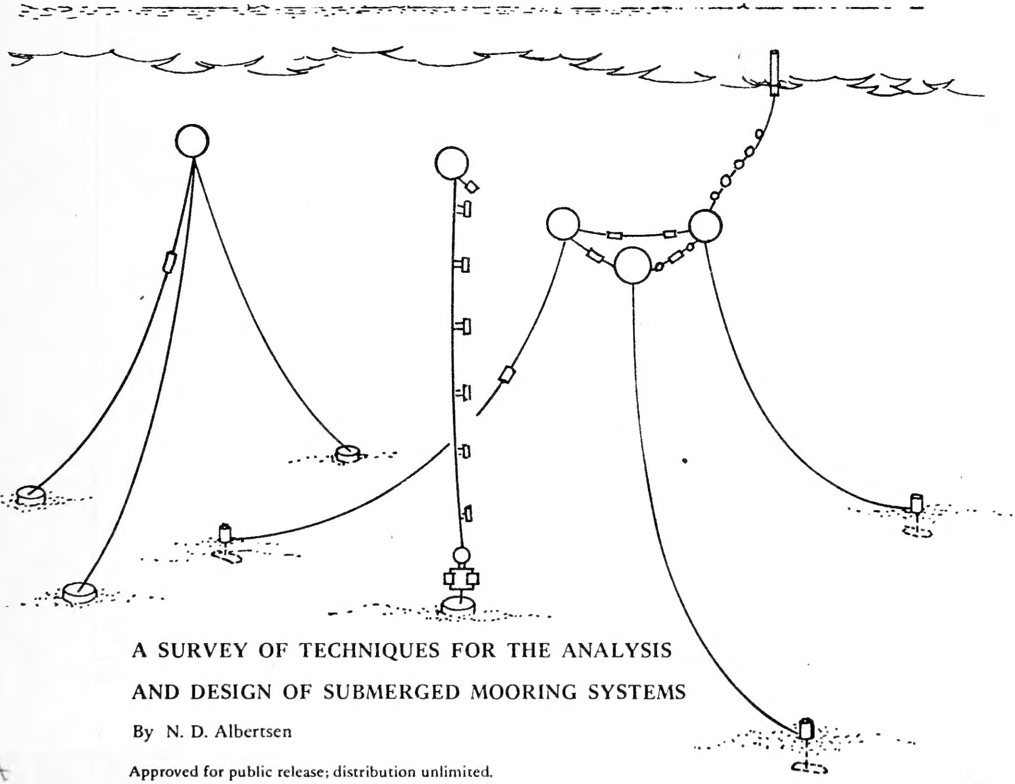
R 815

Sponsored by

NAVAL FACILITIES ENGINEERING COMMAND

August 1974

CIVIL ENGINEERING LABORATORY
NAVAL CONSTRUCTION BATTALION CENTER
Port Hueneme, CA 93043



A SURVEY OF TECHNIQUES FOR THE ANALYSIS AND DESIGN OF SUBMERGED MOORING SYSTEMS

By N. D. Albertsen

Approved for public release; distribution unlimited.

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS
BEFORE COMPLETING FORM

1. REPORT NUMBER
R-815

2. GOVT ACCESSION NO.

3. RECIPIENT'S CATALOG NUMBER

4. TITLE (and Subtitle)
A Survey of Techniques for the Analysis and Design of Submerged Mooring Systems

5. TYPE OF REPORT & PERIOD COVERED
Final; Sep 1972–May 1974

6. PERFORMING ORG. REPORT NUMBER

7. AUTHOR(s)
N. D. Albertsen

8. CONTRACT OR GRANT NUMBER(s)

9. PERFORMING ORGANIZATION NAME AND ADDRESS
CIVIL ENGINEERING LABORATORY
Naval Construction Battalion Center
Port Hueneme, California 93043

10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
62755N
YF53.535.004.01.005

11. CONTROLLING OFFICE NAME AND ADDRESS
Naval Facilities Engineering Command
Alexandria, VA 22332

12. REPORT DATE
August 1974

13. NUMBER OF PAGES
34

14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)

15. SECURITY CLASS. (of this report)
Unclassified

15a. DECLASSIFICATION DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Submerged moorings, cables, computer simulations, cable strumming, static analysis, dynamic analysis, vortex shedding.

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Techniques useful for the design and analysis of moored cable systems are presented. Included are compilations of information describing computer programs for steady-state and dynamic analyses and method for the analysis and suppression of cable strumming. It was found that the steady-state analysis of complex redundant structures and the dynamic analysis of simple structures are now possible. However, experimental data are required to validate the analysis procedures and related computer

continued

20. Continued

programs. In addition, it was found that procedures still need to be developed to reliably predict, describe, and suppress cable strumming in long cables exposed to oceanic conditions.

INTRODUCTION

This survey presents a summary of information for the analysis and design of one class of ocean structure, the moored cable system. The survey is divided into three broad analytical categories: (1) steady-state analysis, (2) dynamic analysis, and (3) cable-strumming analysis and design considerations. The information is presented in a format which will help the engineer select a computer program, analytical model, or design tool which best fits his analysis or design needs.

Three previous surveys on the analysis of cable systems under hydrodynamic loading have summarized steady-state and dynamic models available to mid-1970 [1], summarized some of the new dynamic models to early 1973 [2], and reviewed the various mathematical techniques used in dynamic analysis [3]. The present survey attempts to update and complement these surveys to give a more complete picture of the state-of-the-art of steady-state and dynamic analyses and to present a summary of analytical techniques and design considerations for predicting and suppressing cable strumming.

Figure 1 presents the terminology used in this survey to describe the various mooring types. It is particularly noted that the terms used in Figure 1 to describe the moorings refer to the number of "legs" involved and not the number of buoys.

STEADY-STATE ANALYSIS

Table 1 presents computer programs for the steady-state (static) analysis of moored cable systems. These programs attempt to predict the distribution of stresses in the cables and the geometry of moorings under the action of steady currents or other time-independent forces. Information on how program authors can be contacted and source reference numbers are presented to enable the reader to obtain more details on the programs in which he is interested.

Terminology of Table 1

Each of the descriptive terms used in Table 1 are briefly discussed below.

Program Dimensionality. Programs for the analysis of moored cable systems may be one-, two-, or three-dimensional. However, most steady-state programs are either two- or three-dimensional so that the effects of nonaxial loadings (current forces, etc.) can be accounted for. Two-dimensional programs are useful for the analysis of single-point mooring systems in coplanar force fields. Three-dimensional programs are used in conjunction with multileg structures and nonplanar force fields. Eleven of the 27 entries in Table 1 are two-dimensional, 16 are three-dimensional.

Mooring Type. The terms used to define the mooring are given in Figure 1. Most of the programs in Table 1 are for the single-point mooring only. The program by R. A. Skop is a general one that can be applied to a variety of complex mooring configurations.

Cable Material. A length of cable is compound if its physical or mechanical properties (area, modulus, etc.) vary along its length. A cable is extensible if it stretches under load. Both these cable characteristics are modeled by most of the programs in Table 1.

Current Profile Variation With Depth. Ocean currents at any specific point can vary in magnitude and direction with depth and time. The effects of current variations with time are beyond the capabilities of the static programs unless the changes occur very slowly so that the time-dependent forces are very small. Gross errors can result if ocean-current regimes are not properly modeled by the computer program. The majority of the programs in Table 1 can model variations in current magnitude with depth; 13 programs can model current profiles that vary in magnitude and direction with depth.

Program Validation. None of the programs presented in Table 1 yield exact solutions because of

assumptions associated with the structure and with hydrodynamic loading criteria and because of errors inherent in the computational techniques and machines. Therefore, to provide full confidence in a program it should be validated by comparing predicted results with precise experimental data. However, because little experimental data exists to validate programs, only a few of the programs for the simple mooring types have been validated.

Assumptions. The assumptions vary from program to program but basically center on the method used to model the structure and on the simplifications used in the calculation and application of the hydrodynamic loading forces.

Remarks. A brief summary of program characteristics and capabilities are presented, and the availability of program listings is indicated.

Survey Results

All the programs presented in Table 1 are operational. It should be mentioned that some of the dynamic programs use a steady-state program to establish a starting point for dynamic analysis. The entries in Table 1 based on Reference 16 by Patton and on References 37 and 38 by Goodman and Sargent are examples of static programs which are extracted from a dynamic program.

DYNAMIC ANALYSIS

In this section computer programs for the dynamic analysis of moored cable systems are presented. These programs try to simulate the dynamic response of various moored structures under the action of time-dependent forces other than those produced by vortex shedding. Table 2 presents the programs and attempts to update and complement the surveys presented in References 1 through 3.

Terminology of Table 2

Each of the descriptive terms found in Table 2 are briefly discussed below.

Program Dimensionality. As with the steady-state programs, the dynamic programs may be one-, two- or three-dimensional. The two programs in Table 2 that are one-dimensional examine the behavior of a mooring system along the cable axis. The remaining programs are concerned with tensions and displacement of the system in a plane or in space. The authors of several of the two-dimensional programs feel that extension to the third dimension would not require large amounts of reprogramming. To simulate the ocean environment, particularly near the surface, three-dimensional analysis is many times a necessity because of nonplanar wind, wave, and current forces.

Mooring Type. Again the reader is referred to Figure 1 for definitions of the terms used to describe mooring-system types. Most of the programs listed in Table 2 are for the single-point mooring.

Solution Method. A variety of solution methods are used in the dynamic programs. Reference 3 gives an excellent summary of the methods with their merits and demerits.

System Excitation. The environmental factors which produce the dynamic system response are summarized here. The excitation sources are related to wave, wind, or current.

System Damping. The forces generated by mooring systems which oppose the dynamic response of the systems are called damping forces. Damping is generally hydrodynamic- or cable-related but may be assumed to be a function of the geometry or mass of the system. An excellent presentation of the Voight and Maxwell linear-damping models for cables is given in Reference 40.

Properties of Cables. The assumptions associated with the cables are summarized here. In most cases all forces and mass are assumed to be concentrated at discrete points along the cable. The cables are assumed either to be completely flexible and elastic or to be made up of a series of springs or rigid segments interconnected with springs.

Status of Program. Information on whether the program is operational or proprietary is given.

Remarks. A brief description of the program is given along with information concerning assumptions, computer-time requirements, and where a program listing may be found.

Survey Results

It is evident, after surveying the literature on moored-cable-system analysis in general and dynamic-cable analysis in particular, that two major deficiencies exist. First, experimental data to validate the programs are lacking; without this data, the precision and reliability of the programs are in doubt and, thus, the programs are of limited usefulness. Second, the dynamic programs must be generalized and streamlined so that complex, three-dimensional, moored structures can be analyzed using reasonable amounts of computer time.

CABLE-STRUMMING ANALYSIS AND DESIGN CONSIDERATIONS

When a cable is exposed to crossflow and the resulting Reynold's number lies between 90 and approximately 1×10^6 vortices spring from the sides of the cable, producing a fluctuating fluid pressure. The resulting forces cause the cable to vibrate in a plane normal to the directional fluid flow. This transverse vibration is cable strumming (see References 42, 69, 70, and 71 for descriptions of vortex-shedding, cable strumming phenomenon). Cable strumming in moored-cable systems produces cable fatigue, high acoustic noise levels, and increased drag. These factors all work to the detriment of the mooring and can cause failure or unacceptable performance. Thus, reliable methods for predicting when cable strumming will occur and ways to suppress strumming must be developed.

One way to predict and describe the cable-strumming phenomenon would be to solve the time-dependent Navier-Stokes equations for the three-dimensional separated flow that is characteristic of cable strumming. Unfortunately, such a solution at this time is not possible because the strumming phenomenon still needs to be better understood. What is required is some "tool" that permits reliable prediction and description of cable strumming without being dependent on a complete numerical solution to the Navier-Stokes equations.

Below, information is presented to aid in the analysis and design of moored-cable systems that may be subjected to cable strumming.

Mathematical Oscillator Models

The oscillator models, presented in Table 3, attempt to duplicate the experimentally observed behavior of cables and other bluff bodies in crossflow. None of the models given in Table 3 is capable of predicting or describing cable strumming, but these models form a base of information that, with further development, may result in a predictive tool.

Flow Field Models

Table 4 presents the flow field models which attempt to describe the flow fields near bluff bodies in crossflow. Advanced versions of these models may directly result in predictive and descriptive information for cable strumming; or they may produce new insight into the strumming phenomenon that, in turn, can be applied to the development of predictive or descriptive tools.

Cable-Strumming Design Considerations

This section presents currently available information pertaining to strumming prediction, increased drag due to strumming, and strumming suppression. Though this design information yields only rough approximations, it will show a design engineer how to determine if strumming is probable, what can be done to estimate the resultant increase in drag for short smooth cables, and what methods are available to eliminate strumming.

Strumming Prediction. Experimental studies have shown that flexible cylinders and cables are induced to vibrate by vortex shedding at frequencies approximated by the String Equation [103, 104]. The string equation for vibration in water is:

$$f_n = (n/2L)(T/M_c)^{1/2} \qquad (1)$$

where f_n = natural frequency (Hz)

n = mode number (1, 2, 3 ...)

L = cable length (ft)

T = cable tension (lb)

M_c = virtual mass of cable (slug/ft)

= mass of cable + mass of equivalent volume of water

It has also been shown that the approximate frequency of vortex shedding from relatively short* cylinders and cables perpendicular to flow may be characterized by the Strouhal Equation [103, 104]. The Strouhal relation is

$$f_s = SV_o/d \qquad (2)$$

where f_s = Strouhal frequency (Hz)

S = Strouhal number $\cong 0.2$ when $2 \times 10^2 < R < 1 \times 10^5$

V_o = free stream velocity (ft/sec)

d = diameter of cable (ft)

R = Reynolds Number

When the cable is inclined to the flow by an acute angle θ between the free stream and the cable, then the Strouhal relation is:

$$f_s \cong (SV_o \sin\theta)/d \qquad (3)$$

When the Strouhal frequency is found to be nearly the same as the natural frequency of the cable, the maximum vibration amplitude (for example, the worst strumming) occurs. The first step in investigating a cable segment for its propensity to strumming is to assign preliminary design values to the parameters in the string and Strouhal equations and then to determine if the resulting frequencies are nearly the same. If the frequencies are close, large-amplitude cable strumming may occur; if the frequencies are not close for several mode numbers, vibrations, if present, will probably be of small amplitude.

Increased Drag Due to Strumming. The following equation has been developed to predict the maximum drag coefficient (values for C_D when $f_s \cong f_n$) that can be expected in short sections of a strumming, smooth, circular cable [103, 104]:

$$C_{D_s} = C_D [1 + 10(d^2/M_c)^2] \qquad (4)$$

where C_{D_s} = drag coefficient for strumming cable

C_D = drag coefficient for stationary cable

d = cable diameter (ft)

M_c = virtual mass of cable (slug/ft^3)

Equation 4 has been verified for small-diameter (0.057 in. < d < 0.140 in.) smooth cables of mass per unit length from 1.16×10^{-4} to 9.3×10^{-4} slug/ft over a range of Reynolds numbers from 300 to 1,300. No verification of the equation has been made for stranded cables.

Strumming Suppression. If strumming must be reduced or eliminated in a cable, changes can be made to the cable system so that the natural frequency and Strouhal frequency are much different or a cable fairing can be added to disrupt the vortex-shedding process. Figure 2 shows how four cable fairings compare in terms of strumming drag coefficient and strumming force over a range of Reynolds numbers. In Table 5, several additional fairings are described and performance characteristics listed. It should be noted that for some fairings the drag coefficient is increased over that of a bare cable even though strumming force or vibration amplitude is reduced.

To summarize, analysis and design procedures to predict, describe, and suppress strumming in long cables under oceanic conditions are not possible. Today's procedures consist of comparing the natural frequency of a cable (Equation 1) with the Strouhal frequency for the cable in flow (Equations 2 or 3) to determine if strumming is likely. If strumming is predicted on this basis, changes are made to the system or some fairing is added to the cable.

---

* A short cable is one that does not exhibit large variations in normal velocity component due to either streaming (bending) of the cable or nonuniform current profiles.

CONCLUSIONS AND RECOMMENDATIONS

1. The steady-state analysis of complicated, multileg, redundant, submerged mooring systems is now possible.

2. The dynamic analysis of simple mooring systems, such as the single-point mooring and the bi-mooring is now possible.

3. Precise validation data for the steady-state and dynamic programs are needed to quantify the errors associated with the various techniques and to help select correct hydrodynamic loading criteria and added mass and damping coefficients used in the computer programs.

4. Analysis and design procedures need to be developed to reliably predict, describe, and suppress strumming in long cables in an ocean environment.

5. Experimental data are needed to aid in the development of a reliable tool to predict and describe cable strumming and in the development of practical strumming suppressors.

REFERENCES

1. M. J. Casarella and M. Parsons. "Cable systems under hydrodynamic loading," Marine Technology Society Journal, vol. 4, no. 4, July/Aug. 1970, pp. 27-44.

2. Hydrospace-Challenger, Inc. HCI TR 4450 0001: An inventory of current mathematical models of scientific data-gathering moors, by D. B. Dillon. Rockville, Md., Feb. 1973.

3. Cathodic University of America. Report 73-1: A survey of analytical methods for dynamic simulation of cable-body systems, by Y. I. Choo and M. J. Casarella. Washington, D. C., Mar. 1973.

4. Naval Research Laboratory. Report 7296: The analysis of internally redundant structural cable arrays, by R. A. Skop and G. J. O'Hara. Washington, D. C., Sep. 1971.

5. R. A. Skop and G. J. O'Hara. "The method of imaginary reactions – a new technique for analyzing structural cable systems," Marine Technology Society Journal, vol. 4, no. 1, Jan/Feb. 1970, pp. 21-30.

6. R. A. Skop, "The method of imaginary reactions: applications to N-point moors," Preprints of the Sixth Annual Conference, June/July 1970, vol. 1. Washington, D. C., Marine Technology Society, 1970, pp. 1-22.

7. Naval Research Laboratory. NRL Report 6894: The static configuration of a tri-moored subsurface, buoy-cable array acted on by current-induced forces, by R. A. Skop and R. E. Kaplan. Washington, D. C., 14 May 1969.

8._____ NRL Report 7640: A Fortran IV program for computing the static deflections of structural arrays, by R. A. Skop and J. Mark. Washington, D. C., Aug. 1973.

9. Woods Hole Oceanographic Institution. Report WHOI-73-85: Computer simulation of a tripod mooring for design and prediction, by N. N. Panicker. Woods Hole, Mass., Nov. 1973.

10. Bell Telephone Laboratories. Technical Report No. 14. The analysis of mooring systems and rigid body dynamics for suspended structures, by J. M. Gormally. Whippany, N. J., Dec. 1966.

11. Massachusetts Institute of Technology, Instrumentation Laboratory. Report E-2321: A stress and stability analysis of the pilot project oceanic telescope, by H. F. Little. Cambridge, Mass., Aug. 1968.

12. Naval Underwater Systems Center. Technical Memorandum No. SA2302-323-71: A finite element model of a submerged line array moored in uniform current fields, by J. D. Wilcox. New London, Conn., July 1971.

13. J. W. Bendendender. "Three-dimensional boundary value problems for flexible cables," paper presented at Second Annual Offshore Technology Conference, Houston, Tex., April 1970. (OTC Paper No. 1281).

14. S. Bell, General Electric Co., personal communication: Outline of GE-RESD capability in static and dynamic analysis of mooring systems. Philadelphia, Pa., Jan. 1973.

15. Woods Hole Oceanographic Institution. Report WHOI 68-79: Tension and geometry of single point moored surface buoy system, by W. D. Martin. Woods Hole, Mass., Dec. 1968.

16. Naval Underwater System Center. Technical Report 4331: The response of cable-moored axisymmetric buoys to ocean-wave excitation, by K. T. Patton. New London, Conn., June 1972.

17. D. B. Dillon. Hydrospace-Challenger Inc. cable programs, personal communication: Hydrospace-Challenger Inc., Rockville, Md., Jan. 1973.

18. S. M. Gay. "Computer analysis and design of undersea cable systems," Undersea Technology, vol. 9; no. 10, Oct. 1968, pp. 43-49.

19. Naval Ship Research and Development Center. Report 3692: Effects of Nonplanar current profiles on the configuration of moored cable systems, by H. T. Wang. Bethesda, Md., Oct. 1971.

20. H. T. Wang and B. L. Wester. "Current profiles which give rise to nonunique solutions of moored cable systems," paper presented at the Fourth Annual Offshore Technology Conference, Houston, Tex., May 1972. (OTC Paper No. 1538.)

21. John McChandless, Naval Air Development Center, Sonar Sensor Division. Personal communication: Moor motion analysis at the Naval Air Development Center. Warminster, Pa., Dec. 1972.

22. D. Hubbard, Naval Ordnance Laboratory, White Oak. Personal communication: Moor motion analysis at the Naval Ordnance Laboratory. Silver Spring, Md., Jan. 1973.

23. M. Schreiber, Lockheed Missile and Space Co. Personal communication: Computer programs for the analysis of moored cable systems. Sunnyvale, Calif., Mar. 1973.

24. Lockheed Missile and Space Co. Unpublished document: Ocean systems structural analysis computer capabilities, by H. H. Eiriz. Sunnyvale, Calif., Feb. 1973.

25. Stanford University, Department of Petroleum Engineering, School of Earth Sciences. Report No. : The design and analysis of a submerged, buoyant, anchored pipeline for transporting natural gas through the deep ocean, by G. H. Savage. Stanford, Calif., Aug. 1970. (NSF Contract No. GH-61 and ONR Contract No. N00014-67-A-D158-004)

26. University of New Hampshire, Engineering Design and Analysis Laboratory. Technical Report No. 104: Project Seaspider – Pacific; analysis of the motion of a tri-moored buoy with neutrally buoyant legs, by G. N. Sniffin and G. H. Savage. Durham, N. H., Feb. 1968.

27. John Mariano and A. Shashaty, Bell Laboratories, Cable Placing Group. Personal communication: Moor motion analysis at Bell Laboratories. Whippany, N. J., Dec. 1972.

28. Naval Underwater Systems Center. Technical Report 4379: Nondimensional steady-state cable configurations, by G. T. Griffin. New London, Conn., Aug. 1972.

29. Texas A and M University. COE Report No. 157: Three dimensional response of deep water mooring lines in steady current flow; mechanics of cable mooring systems, vol. I., by R. F. Dominguez and G. E. Owens. College Station, Tex., Dec. 1972.

30._____ COE Report No. 158: Bi and quad cable arrays systems summary data report; Mechanics of cable mooring systems, vol. II, by R. F. Dominguez. College Station, Tex., Feb. 1973.

31._____ COE Report No. 159: Parametric evaluations of bi and quad cable array systems; Mechanics of cable mooring systems, vol. III, by R. F. Dominguez and R. deCastongrene. College Station, Tex., Feb. 1973.

32._____ COE Report No. 160: A computer program for analyzing the steady-state response of bi and quad cable arrays; Mechanics of cable mooring systems, vol. IV, by R. F. Dominguez and N. M. Muska. College Station, Tex., Feb. 1973.

33._____ COE Report No. 161: The response of a tri-moored cable array with an included deformable cylindrical member; Mechanics of cable mooring systems, vol. V, by R. F. Dominguez and G. G. Greer. College Station, Tex., Feb. 1973.

34._____ COE Report No. 162: A computer program for analyzing the steady-state configuration of a tri-moored array with included rigid and deformable members; Mechanics of cable mooring systems, vol. VI, by R. F. Dominguez, G. G. Greer, and A. C. Liau. College Station, Tex., Jan. 1973.

35_____. COE Report No. 163: The steady-state behavior of a pyramid array system; Mechanics of cable mooring systems, vol. VII, by R. F. Dominguez, G. G. Greer and A. C. Liau. College Station, Tex., Mar. 1973.

36. R. F. Dominguez and R. W. Filmer. "Discrete parameter analysis as a practical means for solving mooring behavior problems," paper presented at the Third Annual Offshore Technology Conference, Houston, Tex., Apr. 1971 (OTC Paper No. 1515).

37. National Data Buoy Center. Contract Report NDBCM 6113.1: Static and dynamic analysis of a moored buoy system, by T. R. Goodman, et al. Bay Saint Louis, Miss., Apr. 1972.

38_____. Contract Report NDBCM 6113.2: Computer program documentation report, buoy-cable dynamics program, by T. P. Sargent, A. I. Raff, and J. Bentson. Bay Saint Louis, Miss., Apr. 1972.

39. Naval Ship Research and Development Center. Report 2531: A Fortran IV program for the calculation of a flexible cable in a uniform stream, by Elizabeth Cuthill. Bethesda, Md., Feb. 1968.

40. University of Washington, Department of Civil Engineering, Division of Structures and Mechanics. Technical Report No. SM72: Frequency domain analysis for the tension in a taut mooring line, by S. T. Hong. Seattle, Wash., July 1972.

41. L. H. Seidl. "On the dynamics of a mooring line," Look Lab/Hawaii, vol. 2, no. 1, Jan. 1971, pp. 11-22.

42. Naval Ordnance Laboratory, White Oak. TR-72-77: Cable strumming – some energy estimates for a moored mine system, by G. E. Hudson. Silver Spring, Md., Jan. 1973.

43. W. Nerenstein and J. Nowatzki, Bendix Electrodynamic Corp. Personal communication: Analysis of moored cable systems at Bendix Corp. Sylmar, Calif., Apr. 1973.

44. G. M. Research Laboratory. TR 65-79: The dynamics of simple deep-sea buoy moorings, by R. G. Paquette and B. E. Henderson. Santa Barbara, Calif., Nov. 1965.

45. C. S. Draper Laboratory. Report R (in preparation): Mooring mechanics – a comprehensive computer study (Part I. Surface moorings; Part II. Subsurface moorings), by N. K. Chhabra. Cambridge, Mass., 1974.

46. P. Y. Chang and W. D. Pilkey. "Static and dynamic analysis of mooring lines," Journal of Hydronautics, vol. 7, no. 1, Jan. 1973, pp. 29-34.

47_____. "The analysis of mooring lines," paper presented at Offshore Technology Conference, Houston, Tex., Apr. 1971 (OTC Paper No. 1502).

48. Woods Hole Oceanographic Institution. WHOI-73-22: Computer program for the static analysis of single point moored surface and subsurface buoy systems, by H. O. Berteaux and N. K. Chhabra. Woods Hole, Mass., Mar. 1973.

49. D. J. Bennett, Bunker-Ramo, Electronic Systems Div., Government Systems Group. Personal communication: Mooring analysis at Bunker-Ramo. Westlake Village, Calif., 20 July 1973.

50. Bunker-Ramo, Electronic Systems Division, Government Systems Group. Brochure No. 5240-338. VLAM-A multichannel acoustic measurement system, Westlake Village, Calif.

51. Swede Momson, G. M. Research Defense Laboratory. Personal communication: Cable analysis capabilities at G. M. Research Defense Laboratory. Santa Barbara, Calif., Jan. 1973.

52. H. C. Merchant and M. A. Kelf. "Nonlinear analysis of a submerged ocean buoy system," an abstract of a paper to be presented at Ocean 73, Seattle, Wash., Sept. 1973. (Abstract dated 19 Jan. 1973.)

53. M. A. Kelf. Non-linear analysis of submerged ocean buoy systems, M. S. thesis, University of Washington, Seattle, Wash., 1973.

54. N. T. Tsai. "Analysis of nonlinear transient motion of cables using bond graph method," Transactions of the ASME Journal of Engineering for Industry, May 1972.

55. N. T. Tsai, General Dynamics. Personal communication: Numerical models of mooring systems at General Dynamics. San Diego, Calif., Feb. 1973.

56. Naval Ship Research and Development Center. NSRDC Report No. 3663: A two-degree-of-freedom model for the two-dimensional dynamic motions of suspended extensible cable systems, by H. T. Wang. Bethesda, Md., Oct. 1971.

57. Naval Air Systems Command. Report No. T72-AV-9602-V: Sonobuoy cable system analysis, by D. R. Sanders and M. L. Collier. Washington, D. C., Tracor Corp., Nov. 1972. (Contract N00019-72-C-0239).

58. R. A. McLauchlan, et al. "A dynamic analysis of moored and free-floating cable systems," paper presented at the Fifth Annual Offshore Technology Conference, Houston, Tex., Apr. 1973. (OTC Paper No. 1742)

59. R. D. Taylor. An analytic model to predict the dynamic loading of a cable system in a linearly varying current profile, M. S. thesis, University of Texas, Austin, Tex., May 1973.

60. W. D. Iwan. "Dynamic response of suspended underwater systems," Journal of the Acoustical Society of America, vol. 51, no. 5, Part 2, 1972, pp. 1688-1696.

61. R. F. Dominguez and C. E. Smith, "Dynamic analysis of cable systems," Journal of the Structural Division, American Society of Civil Engineers, vol. 98, no. ST8, Aug. 1972, pp. 1817-1834.

62. B. W. Wilson and D. H. Garbaccio. "Dynamics of ship anchor-lines in waves and current," Journal of the Waterways and Harbors Division, ASCE, vol. 95, no. WW4, Nov. 1969, pp. 449-463.

63. Catholic University of America. Report 72-5: The dynamics of a ship moored by a cable system under sea state excitation, by E. E. Zarnick and M. J. Casarella. Washington, D. C., July 1972.

64. E. E. Zarnick. The dynamics of a ship moored by a cable system under sea state excitation, Ph.D. thesis, Catholic University of America. Washington, D. C., 1972.

65. Naval Civil Engineering Laboratory. Technical Note N-1053: Dynamic line force and oscillatory motion of a vessel being winched down in ocean – two computer solutions, by C. L. Liu and J. A. Drelicharz. Port Hueneme, Calif., Oct. 1969.

66. National Data Buoy Center. National Ocean Survey. Unnumbered report: A new technique for the solution of the equations of cable dynamics for the NDBC buoy-cable dynamics simulation, by A. Trampus. Rockville, Md., Dec. 1972.

67. R. Blumberg and C. D. Osborn. "Computer-aided design of submerged ocean buoy systems," paper presented at the First Annual Offshore Technology Conference. Houston, Tex., May 1969. (OTC Paper No. 1133)

68. C. S. Draper Laboratory. Report in preparation: Mooring dynamics experiment: determination of a verified dynamic model of the W.H.O.I. intermediate mooring, by N. Chhabra, et al. Cambridge, Mass., 1974.

69. J. R. Dale and R. A. Holler. "Spurious signals from cable-suspended sonar systems," Journal of Hydronautics, vol. 3, no. 2, Apr. 1969, pp. 83-87.

70. A. W. Marris. "A review on vortex streets, period wakes, and induced vibration phenomena," Journal of Basic Engineering, vol. 86, series D, no. 2, June 1964, pp. 185-196.

71. M. V. Morkovin. "Flow around circular cylinder – a kaleidoscope of challenging fluid phenomena," paper presented at American Society of Mechanical Engineers Symposium on Fully Separated Flow. Philadelphia, Pa., May 1964.

72. I. Dyer, Massachusetts Institute of Technology. Personal communication: Dynamic response of deep mooring systems. Cambridge, Mass., June 1973.

73. I. L. Ver. "Power balance and statistical energy analysis," Proceedings of Intersociety Energy Conversion Engineering Conference, Boston, Mass., Society of Automotive Engineers, Inc., Aug. 1971, pp. 1041-1047.

74. The Shock and Vibration Information Center. Monograph SVM-1: Random noise and vibration in space vehicles, by R. H. Lyon. Superintendent of Documents, U.S. Government Printing Office, Washington, D. C., 1967.

75. R. H. Lyon. "Statistical analysis of power injection and response in structures and rooms," The Journal of the Acoustical Society of America, vol. 45, no. 3, June 1967, pp. 545-565.

76. Y. Nakamura. "Vortex excitation of a circular cylinder treated as a binary flutter," Reports of Research Institute of Applied Mechanics, vol. XVIII, no. 59, 1969. (Kyushu University, Kushu, Japan,) pp. 217-234.

77. M. Funakawa. "Excitation mechanism of an elastically supported circular cylinder in a flowing fluid," Bulletin of Journal of Society of Mechanical Engineers, vol. 35, no. 270, 1969, p. 303.

78. C. S. Draper Laboratory. Report in preparation: Lumped parameter representation of Karman vortex excitation, by D. G. Shepard. Cambridge, Mass., 1973.

79. G. D. Silvo. "Self-controlled vibration of a cylinder in fluid stream," Journal of Engineering Mechanics Division, ASCE, vol. 95, no. EM2, Apr. 1969., pp. 347-361.

80. H. Halle. "Proposed analytical model for the cross-flow-induced vibrations of a circular cylinder," in Proceedings of Conference on Flow-Induced Vibrations on Reactor System Components, Argonne National Laboratory, Argonne, Ill., May 1970. (Argonne Laboratory Report ANL-7685).

81. R. T. Hartlen and I. G. Currie. "Lift oscillator model of vortex-induced vibration," Journal of Engineering Mechanics Division, ASCE, vol. 96, no. EM5, Oct. 1970, pp. 577-591.

82. I. G. Currie, R. T. Hartlen, and W. W. Martin. "The response of circular cylinders to vortex shedding," paper presented at Symposium on Flow-induced Structural Vibration, Karlsruhe, Germany, Aug. 1972.

83. S. Kawamura. "A design criterion — wind loads of high steel stacks," Proceedings of the Third International Conference on Wind Effects on Buildings and Structures, Tokyo, Japan, 1971, pp. 707-716.

84. R. A. Skop and O. M. Griffin. "An hueristic model of determining flow induced vibrations of offshore structures," paper presented at the Fifth Annual Offshore Technology Conference, Houston, Tex., Apr. 1973. (OTC Paper No. 1843).

85. O. M. Griffin, R. A. Skop, and G. H. Koopman. "Measurement of the response of bluff cylinders to flow-induced vortex shedding," paper presented at the Fifth Annual Offshore Technology Conference, Houston, Tex., Apr. 1973. (OTC Paper No. 1814).

86. R. A. Skop and O. M. Griffin. "A model for the vortex-excited resonant response of bluff cylinders," Journal of Sound and Vibration, vol. 27, no. 2, March 1973, pp. 225-233.

87. W. D. Iwan and R. Belvins. Unpublished Manuscript. A model for vortex induced oscillation of structures, California Institute of Technology, Pasadena, Calif., Dec. 1973.

88. J. E. Fromm and F. H. Harlow. "Numerical solution of the problem of vortex street development," The Physics of Fluids, vol. 6, no. 7, July 1963, pp. 975-982.

89. D. C. Thoman and A. A. Szewczyk. "Time-dependent viscous flow over a circular cylinder," High-Speed Computing in Fluid Dynamics — The Physics of Fluids Supplement II, 1969, pp. II-76 to II-86.

90. T. Sarpkaya. "An analytical study of separated flow about circular cylinders," Journal of Basic Engineering, Dec. 1968, pp. 511-520.

91. T. Sarpkaya, Naval Postgraduate School. Personal communication: Flow field studies at the Naval Postgraduate School. Monterey, Calif., Mar. 1973.

92. A. D. K. Laird. "Eddy formation behind circular cylinders," Journal of the Hydraulics Division, ASCE, vol. 97, no. HY6, June 1971, pp. 763-775.

93. A. D. K. Laird, University of California at Berkeley. Personal communication: Recent work on the vortex shedding phenomenon. Berkeley, Calif., Mar. 1973.

94. S. K. Jordan and J. E. Fromm. "Oscillatory drag lift and torque on a circular cylinder in a uniform flow," The Physics of Fluids, vol. 15, no. 3, Mar. 1973, pp. 371-376.

95. R. R. Clements. "An invisced model of two-dimensional vortex shedding," Journal of Fluid Mechanics, vol. 57, part 2, 1973, pp. 321-337.

96. Y. N. Chen. "Wake swing and vortex shedding in a cross flow past a single circular cylinder," paper presented at the Symposium on Flow-induced Structural Vibrations, Karlsruhe, Germany, IAHR and IUTAM, Aug. 1972.

97. J. S. Son and T. J. Hanratty. "Numerical solution for the flow around a cylinder at Reynolds numbers of 40, 200, and 500," Journal of Fluid Mechanics, vol. 35, part 2, 1969, pp. 369-386.

98. J. H. Gerrard. "The stability of unsteady axisymmetric incompressible pipe flow close to a piston, Part 1. Numerical analysis," Journal of Fluid Mechanics, vol. 50, part 1, 1971, pp. 625-644.

99._____ "The low frequency components of separated flows," paper presented at Symposium on Flow-induced Structural Vibrations, Karlsruhe, Germany, IAHR and IUTAM, Aug. 1972.

100. J. Shioiri. "Synchronization phenomenon in vortex shedding and its role in vortex induced oscillations of structures," in Proceedings of the Third International Conference on Wind Effects on Buildings and Structures, Tokyo, Japan, 1971.

101. North American Rockwell Corp. Report SD-68-996: Hydroelastic analysis of a circular cylinder, by B. H. Ujihara. Seal Beach, Calif., Dec. 1968. (Contract N0014-68-C-0223)

102._____. Report SD-69-558: Hydroelastic analysis of a circular cylinder/lift on bodies of revolution, by H. D. McLaughlin and B. H. Ujihara. Seal Beach, Calif, Dec. 1969. (Contract N00014-68-0223)

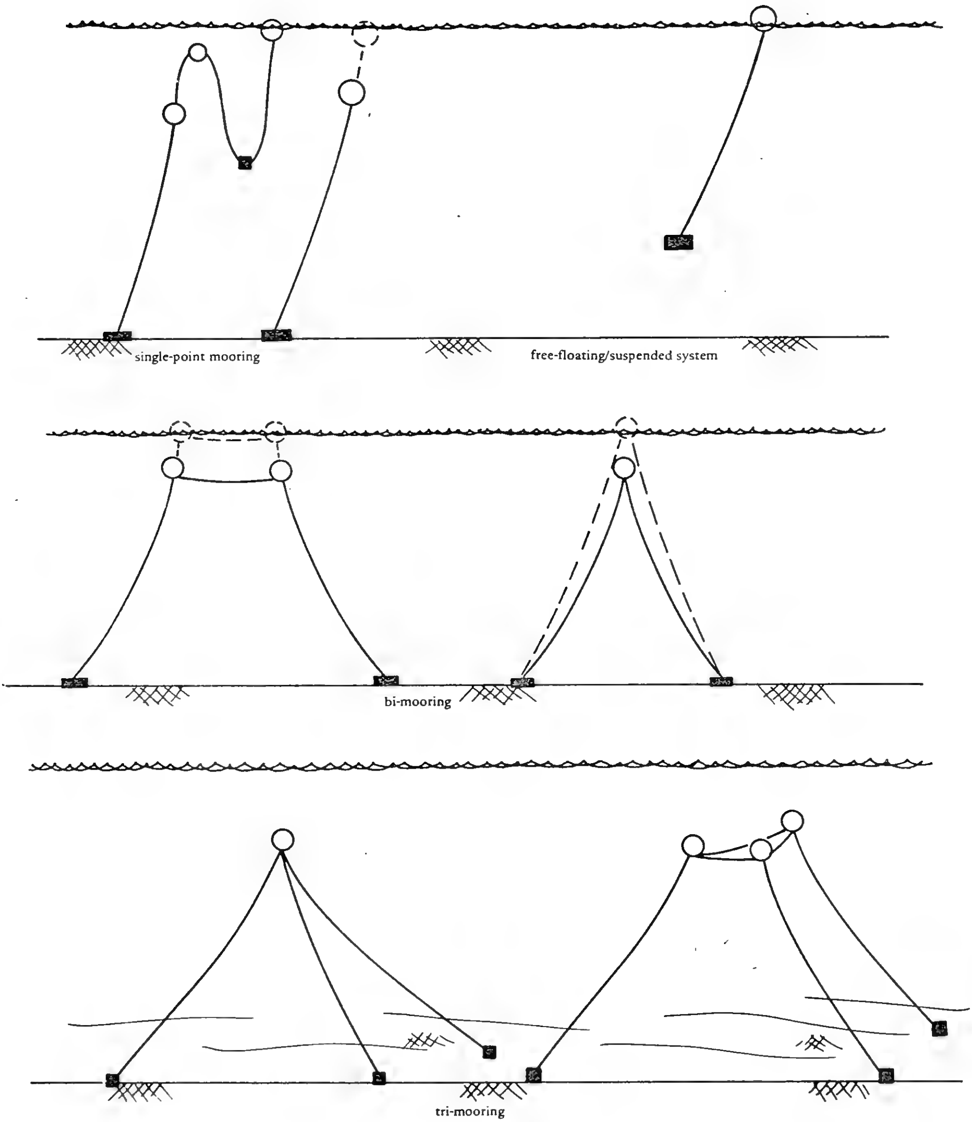
103. Naval Air Development Center. Report No. NADC-AE-6719: Determination of normal drag coefficients for flexible cables," by J. R. Dale. Warminster, Pa., June 1967.

104. Naval Air Development Center. Report No. NADC-AE-6731: Water drag effects of flow induced cable vibrations, by J. R. Dale, J. M. McChandless, and R. A. Holler. Warminster, Pa., Aug. 1967.

105. Naval Mine Defense Laboratory. Interim Report i-132: Drag and vibration of some wire ropes and fairings," by R. E. Kelly and C. N. Goff. Panama City, Florida, Sep. 1967.

106. Naval Ship Research and Development Center. Unpublished manuscript: Vortex induced vibration of bare and ribbon cables. Bethesda, Md., Sep. 1971. Robert Blevins.

107. A. Fabula, Naval Underwater Center. Personal communication: Suppression of cable strumming in towed systems using helical strakes. San Diego, Calif., Feb. 1973.



Note: A General Program is one which can simulate the behavior of the above moorings plus others of additional complexity.

Figure 1. Mooring type terminology.

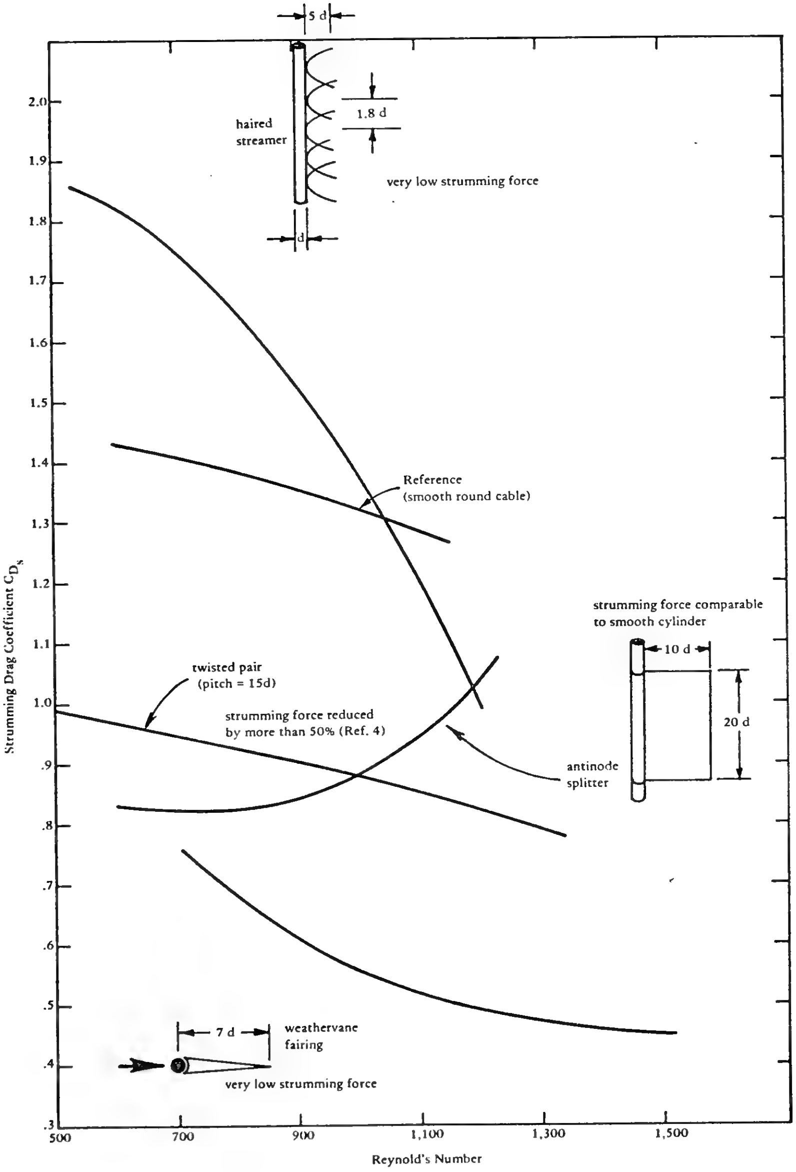


Figure 2. Strumming drag characteristics as found in Reference 106.

Table 1. Steady-State Programs

Author Organization Telephone Number	Program Dimensionality	Mooring Type	Cable Material		Current Profile Variation With Depth		Program Validation	Assumptions	Remarks	Ref No
			Compound Cables	Extensible Cables	Magnitude	Direction				
Dr. R. A. Skop Naval Research Laboratory Washington, D.C. Comm (202) 767-2904 Autovon 297-2904	3	General	yes	yes	yes	yes	no	A. Cables are a series of elements. B. Current profile is linear on each cable element. C. Cables cannot transmit moment. D. Tangential drag force is zero. E. The mooring must be completely submerged or the location of surface devices must be completely specified. F. No cables or cable segments can lie on the ocean floor.	Based on an iterative technique called the Method of Imaginary Reactions (MIR), this very general program can handle complex structures with internal redundant elements and still reach a solution rapidly. All forces on the structure must be known; and sufficient reactions must be known, or assumed, to make the structure statically determinate. Assumed reactions provide a starting point, and these are corrected during each iteration until a predetermined level of accuracy has been reached. Position-dependent forces are handled by using successive approximations. The MIR technique is used by most people for static analysis of multileg mooring systems. The latest version of this program is able to analyze complex mooring configuration with up to 22 cables under any current profile. A computer program listing of the latest version of this technique is given in Reference 8.	4-8
Dr. N. N. Panicker Department of Ocean Engineering Woods Hole Oceanographic Institute Woods Hole, MA Comm (617) 548-1400 Ext. 417	3	Tri-moor	yes	yes	yes	no	no	A. Cables are a series of straight elements. B. A lumped parameter representation of the structure is used. C. Tangential drag coefficient is 2.5% of the normal drag coefficient. D. Cables cannot transmit moment.	This program, based on Skop's MIR (Reference 4), was used to perform design and performance studies on the Woods Hole Internal Wave Experiment (IWEX) tri-mooring. Discrete elements and normal and tangential drag forces could be handled, but not internally redundant structures. Reference 9 does not provide a program listing.	9
Dr. J. M. Gormally Bell Telephone Laboratory Whippany, New Jersey Now with TRW Systems Group Washington Operations McLean, VA Comm (703) 893-2000	3	General without internal redundants	no	yes	no	no	no	A. Current loading on cables are distributed and are constant in magnitude and direction.	A Newton-Raphson iteration procedure is used to solve the fundamental equilibrium and compatibility equations for single, bi-, and tri-moored cable systems without internal redundants. Included are the effects of normal and tangential drag forces. The procedure was set up for operation on the General Electric (GE) Desk Side Computer System (DSCS). Assumption A may cause the results to be grossly in error if the program is applied to a case where currents vary in magnitude and direction with depth.	10
H. Forbes Little Instrumentation Laboratory Massachusetts Institute of Technology Cambridge, MA	3	Bi-moor Tri-moor	yes	yes	yes	yes	no	A. Cables are a series of straight-lined segments. B. Drag force on the cable is computed assuming the projected cable area.	SEASNAKE uses a solution method similar to Skop's MIR. The basic computational element is a cable-integration routine. integration along the cables is used for an initial estimated tension and then the tension estimates are refined based on how far away cable ends are from mooring points after an iteration. The bi- and tri-mooring configurations without internal redundants are handled as are discrete elements on the cables, but the program appears to require more computer time to reach a solution with Reference 8. A program listing is not presented in Reference 11.	11

continued

Table 1. Continued

Author Organization Telephone Number	Program Dimensionality	Mooring Type	Cable Material		Current Profile Variation With Depth		Program Validation	Assumptions	Remarks	Ref No.
			Compound Cables	Extensible Cables	Magnitude	Direction				
John D. Wilcox Naval Underwater Systems Center Newport, RI 02840 Autovon 636-2142	3	Bi-moor	yes	yes	no	no	no	A. Cables are a series of straight segments. B. The cables are perfectly elastic and can sustain neither compressive loads or bending torsional moments. C. Tangential drag force is zero.	This is a three-dimensional, finite-element program for the analysis of bi-mooring arrays under a uniform current. No effort has been made to generalize the program to other mooring types or to include the effects of nonuniform currents; however, the technique appears to have potential in these areas. A program listing is given in Reference 12.	12
John W. Bedendender Texas Instruments Inc. Petroleum Exploration Division P.O. Box 5621 Dallas, TX 75222	3	Single-point moor	yes	no	yes	yes	yes	A. Cables are completely flexible and inextensible. B. The cable ends are subject to constant tension.	This program solves for the steady-state, equilibrium position of a cable when boundary conditions are specified at two locations on the cable. Based on the Adam-Moulton prediction-corrector integration method with a Runge-Kutta starter, the program solves for the boundary-value condition directly rather than by integrating a family of initial-value problems and then selecting the desired solution. It utilizes the differential equations of cable equilibrium that result from three-dimensional velocity fields and hydrodynamic loading functions. This technique should be useful for simple systems, both moored and towed. Attempts to validate the program with towed system data have shown "fair agreement" between actual and predicted data. The program is considered proprietary, and no listings are available.	13
Sam Bell General Electric Corporation Reentry Systems Division Philadelphia, PA Comm (215) 823-5362	3	Tri-moor	yes	yes	yes	yes	yes	A. Cables are a series of straight elements. B. Cables can transmit no moment. C. Cable mass and drag force are lumped on each cable segment.	This is an iterative, finite-element solution technique that begins at any point on the cable system where conditions are known or assumed and that then integrates through the system. When the boundaries of the system are reached, the calculated boundary conditions are compared with the actual conditions, and corrections are then made to the starting-point conditions. The integration process is repeated until calculated and actual boundary conditions agree within some limit of error. The program can handle discrete elements along the cables, and provisions have been made to include aerodynamic drag if it should be needed. Because the program is considered proprietary by GE, some program details and capabilities are not known. Validation of the program by GE with model and full-scale data has shown the program to be "very good."	14
Wayne D. Martin Woods Hole Oceanographic Institution Woods Hole, MA	2	Single-point moor	yes	yes	yes	no	no	A. Cable is a series of 100 straight segments. B. Tangential cable drag coefficient is 2% of the normal drag coefficient.	Developed to determine the steady-state geometry and cable tensions in single-point, mooring systems, this program is based on an iterative, numerical-integration routine for the cable equations. Consideration is given to discrete elements along the cable and to current profiles	15

continued

Table 1. Continued

Author Organization Telephone Number	Program Dimensionality	Mooring Type	Cable Material		Current Profile Variation With Depth		Program Validation	Assumptions	Remarks	Ref No.
			Compound Cables	Extensible Cables	Magnitude	Direction				
Wayne D. Martin (cont'd)								C. Cable mass and drag forces are lumped on each cable segment.	that vary only in magnitude with depth. The program was written for a surface-buoy system but, with only minor changes, could be made applicable to a submerged mooring. A program listing is given in Reference 15.	
Kirk T. Patton Ocean Science Department Naval Underwater Systems Center New London, CT Comm (203) 442-0771 Ext. 2806 Autovon 636-2806	3	Single-point moor	yes	yes	yes	yes	yes	A. Cable is a series of straight elements. B. Cables are perfectly flexible.	This program is a zero-order form of a dynamic program for the behavior of surface-buoyed, single-point moorings. The time-dependent terms in the cable equations have been allowed to go to zero and have then been integrated, using a fourth-order Runge-Kutta integration algorithm. Since the forces on the buoy are a function of cable tension, an iterative solution must be used to match the computed vertical projection of the cable with the depth of water. Program-predicted data show good agreement with data from shallow- and deep-water, single-point moorings.	16
David B. Dillon Hydrospace-Challenger Inc. Rockville, MD Comm (301) 948-4350 Ext. 308	3	Single-point moor; Bi-moor; Tri-moor	yes	yes	yes	yes	yes	A. Cable is a series of straight segments. B. Current profile is linear on each segment.	The modeling capability consists of a program for the initial value problem of a single-point mooring and a program for multileg mooring systems. The initial value program solves the differential equations for cable equilibrium using a numerical-integration technique. The output from this program has been shown to be within 10% of experimental towing cable data. The multileg program uses a technique similar to Skop's MIR with "an improved convergence capability," but the program requires that all legs join at one buoy. The programs are considered proprietary, and no listings are available.	17, 18
Dr. Henry T. Wang Naval Hydromechanics Division, Code 1552 Naval Ship Research and Development Center Bethesda, MD Comm (301) 227-1410 Autovon 287-1410	3	Single-point moor	yes	yes	yes	yes	no	A. The current profile is assumed to be linear between points of interest.	Two steady-state programs have been developed to evaluate the three-dimensional behavior of the single-point mooring. One program (named MR3E) solves the initial value problem of finding the cable scope required to reach a given depth (or depth for a given scope) when the buoyancy and drag are specified for the surface buoy. In cases where both the ocean depth and cable scope are fixed, the correct submergence of the buoy must be determined by iteration. The other program (named MR3S) incorporates the iteration scheme and simply increases buoy draft if the end of the cable does not reach the seafloor or decreases buoy draft if the cable overshoots the seafloor. Both programs use a Kutta-Merson subroutine to integrate the differential equations of cable equilibrium. This program is being used at the Naval Air Development Center and the Naval Ordnance Laboratory for the analysis of moored systems. Program listings are not given in the references.	19-22

continued

Table 1. Continued

Author Organization Telephone Number	Program Dimensionality	Mooring Type	Cable Material		Current Profile Variation With Depth		Program Validation	Assumptions	Remarks	Ref No.
			Compound Cables	Extensible Cables	Magnitude	Direction				
Herb Schreiber Hydrodynamics Department Lockheed Missile and Space Company Sunnyvale, CA Comm (408) 742-0907	2	Single-point moor; Bi-moor	yes	yes	yes	yes	no	A. Cables are a series of straight segments. B. Cables are perfectly flexible.	Lockheed has developed two two-dimensional, steady-state, computer programs for the behavior of single-point mooring systems. The first program is based on Runge-Kutta integration of the differential equilibrium equations for the cable. This program accounts for the effects of currents that vary in magnitude with depth and for discrete elements on the cable. The second program has basically the same capabilities except it can handle the bi-mooring configuration with the end-fire current and is based on the finite-element technique. A three-dimensional finite-element program for the dynamics of complex mooring systems is being developed which will also permit steady-state analysis. The programs are proprietary, and no listings are available.	23, 24
Dr. Godfrey H. Savage University of New Hampshire Durham, NH Comm (603) 862-1356	3	Tri-moor	yes	yes	yes	no	no	A. Cables are a series of straight segments. B. Cable mass and forces on cables are lumped at center of straight cable segments.	This program is based on Skop's MIR and has been used to analyze the behavior of a submerged buoyant pipeline and the tri-mooring cable structures that support and restrain the pipeline. The tri-mooring program assumes that the cable legs are neutrally buoyant and that the current produces no aerodynamic lift on the stranded cable legs. A listing of the programs for pipeline and tri-mooring analysis are given in Reference 25. Prior to the adoption of the MIR for design and analysis of multi-leg mooring systems, Savage and Sniffin developed a program for the analysis of tri-moored, cable structures with neutrally buoyant legs. This program required that the current be unidirectional and constant in magnitude with depth and that the drag on the cables not be affected by the position of the cable. These assumptions made this program less useful and accurate than the more recent program based on the MIR but this program is helpful in providing insight into the problems associated with multi-leg mooring systems. A listing of this program is given in Reference 26.	25, 26
John Mariano Cable Placing Group Bell Laboratory Whippany, NJ Comm (201) 386-4139	3	Single-point moor; Bi-moor; Tri-moor	yes	yes	yes	yes	no	A. Same as other programs based on the Method of Imaginary Reactions.	This program is based on Skop's MIR. The program is proprietary and no listings are available.	27
Gary T. Griffin Ocean Science Department Naval Underwater Systems Center New London, CT Autovon 636-2806	3	Single-point moor	no	no	no	no	no		This is not a computer program but rather a design tool for single-point mooring systems based upon dimensionless coefficients generated from the steady-state cable equations and is included for completeness. The	28

continued

Table 1. Continued

Author Organization Telephone Number	Program Dimensionality	Mooring Type	Cable Material		Current Profile Variation With Depth		Program Validation	Assumptions	Remarks	Ref No
			Compound Cables	Extensible Cables	Magnitude	Direction				
Gary T. Griffin (cont'd)									dimensionless coefficients for drag, cable weight, excess buoyancy-to-tension ratio, spatial coordinates, and buoy geometry are plotted so that, for a given set of buoy and cable parameters and specific current profiles, the horizontal and vertical excursions of the buoy can be determined.	
Professor Richard F. Dominquez Texas A&M University Austin, TX Comm (713) 845-4515	3	Single cable: Bi-moor, Tri-moor, Quad-moor systems with rigid or deformable inclusions	yes	yes	yes	yes	no	A. Cables are a series of straight segments. B. Modified Whicker Model is used for hydrodynamic loading.	Five Fortran computer programs, based on the MIR, have been written for a single cable fixed at both ends, a bi-moored and quad-moored rigid horizontal inclusion, a tri-moored rigid or deformable slender inclusion, and a tri-moored rigid delta. These programs and the subroutines needed to account for the rigid or deformable elements are documented with explanatory information, sample output from a parametric analysis, and program listings in References 29 through 36.	29-36
T. R. Goodman, et al. Oceanics, Inc. for National Data Buoy Center Mississippi Test Facility Bay St. Louis, MS Comm (516) 694-6900	2	Single-point moor	yes	no	yes	no	no	A. Buoy is at the surface and is acted upon by coplanar wind wave and current forces.	This program is for the steady-state analysis of single-point, moored, surface-buoy systems and serves as the starting point for a small-perturbation, dynamic analysis. The equations that define the static equilibrium of the buoy-cable system are set up for solution as a two-point, boundary-value problem and are solved by repeated integration of the equations until the conditions at the buoy and at the anchor are correct. The program can account for discrete elements and for changes in cable characteristics along its length. A flow chart and a program listing (subroutine STATIC) are given in Reference 38.	37-38
Elizabeth Cuthill Naval Ship Research and Development Center Washington, D.C. Comm (202) 227-1302	2	Single-point moor or towed cable	yes	no	yes	no	no	A. Cable is a series of straight segments.	This program was developed for the analysis of towed cables but is applicable to the single-point, mooring system under the action of unidirectional current. The program was developed to use a variety of hydrodynamic-loading functions and can account for cables made up of segments that have parameters which change from segment to segment. The equations of equilibrium for the cables are numerically integrated using a Kutta-Merson variant of the Runge-Kutta method. The technique adjusts the integration step size automatically to maintain a specified estimated accuracy during the integration. A detailed description of the program, a program listing, and sample problems are given in Reference 39.	39

continued

Table 1. Continued

Author Organization Telephone Number	Program Dimensionality	Mooring Type	Cable Material		Current Profile Variation With Depth		Program Validation	Assumptions	Remarks	Ref No.
			Compound Cables	Extensible Cables	Magnitude	Direction				
S. T. Hong University of Washington Seattle, WA Comm (206) 543-2150	2	Single-point moor	yes	yes	yes	no	no	A. Cable is a series of straight elements.	This program is for the steady-state analysis of single-point mooring systems with a surface buoy under the action of a unidirectional current and coplanar winds. The program includes the effects of normal and tangential drag, discrete elements along the cable, and cable extension. Solution begins by assuming an angle of inclination for the cable at the buoy and fits the cable to the water depth using an iterative process with wind and current drag forces as input. A program description and listing are given in Reference 40.	40
Ludwig H. Seidl J.K.K. Look Laboratory of Oceanographic Engineering University of Hawaii Comm (808) 948-8198	3	Single-point moor	yes	yes	yes	yes	no	A. Cables are a series of straight elements. B. Cable mass is lumped along the cable.	This program is for the steady-state behavior of single-point mooring systems under the action of wave and current forces. The program is based on a lumped mass model of the cable and elemental packages and uses a Continuous System Model Program (CSMP) which allows analog-like simulation with a digital computer. The program does not require sophisticated integration routines because integrators are built into the CSMP system, however, computer time can be quite high. A listing of the program can be obtained from the author.	41
George F. Hudson Naval Ordnance Laboratory White Oak Silver Springs, MD Comm (301) 434-7100 Autovon 632-8651	2	Single-point moor	yes	yes	yes	no	no	A. The cable can support a small bending moment. B. Only normal drag is considered.	This program (No. H21032) is for the steady-state analysis of a single-point, moored, submerged, cylindrical "buoy" under the action of a current that may vary in magnitude with depth. The cable is assumed to be semirigid and to be made up of a straight section of cable at the bottom and a section approximated by a circular arc at the top. Solution for cable shape and tension and buoy inclination is by integration of the differential equations of cable equilibrium. A description of the program without a listing is given in Reference 42.	42
Will Nerenstein Bendix, Electrodynamic Division Sylmar, CA Comm (213) 367-0111 Ext. 2454	2	Single-point moor	yes	yes	yes	no	no		This program is for the steady-state analysis of single-point mooring systems in a unidirectional current. The program solves the equations of static equilibrium for the cable by Runge-Kutta integration. Both normal and tangential drag are considered The program is considered proprietary; therefore, some details are not known. No listing is available.	43
Robert G. Paquette GM Research Laboratory Santa Barbara, CA Now at Naval Postgraduate School Monterey, CA Comm (408) 646-2553	2	Single-point moor	yes	yes	yes	no	no	A. Cable is a series of straight spring segments. B. Wind and current are coplanar. C. Mass and force are represented as lumps.	This program uses analog simulation to solve the set of second-order partial differential equations associated with single-point mooring systems under the action of wind and current forces that are unidirectional and coplanar. The cable is simulated by up to 10 straight	44

continued

Table 1. Continued

Author Organization Telephone Number	Program Dimensionality	Mooring Type	Cable Material		Current Profile Variation With Depth		Program Validation	Assumptions	Remarks	Ref No
			Compound Cables	Extensible Cables	Magnitude	Direction				
Robert G. Paquette (cont'd)								D. Nodes have no vertical excursion. E. Tangential drag coefficient equals 2% of the normal drag coefficient.	segments joined at node points where all forces and mass are assumed to be lumped. The computer used was a Pace Model 231-R, a block diagram showing analog implementation of the upper two nodes of the system is given with an explanation in Reference 44.	
N. K. Chhabra Charles Stark Draper Laboratory Massachusetts Institute of Technology Cambridge, MA Comm (617) 258-1316	3	Single-point moor	yes	yes	yes	yes	yes		This program uses the finite element approach to determine line tension and deflections in a single-point, moored cable with either a surface or subsurface buoy. A report (Reference 45) documenting the technique and the program is in preparation.	45
Pin Yu Chang Com/Code Corporation Alexandria, VA Comm (703) 750-1112 Walter D. Pilkey University of Virginia Charlottesville, VA	2	Single-point moor	yes	yes	yes	no	no		This program is based on a technique that first obtains an initial equilibrium configuration for the mooring by explicit integration of the nonlinear equilibrium equations with only the dominant loading included. For most moors, the dominant loading would be the normal hydrodynamic loading but may be other loads such as buoyancy. After the initial configuration has been established, other loadings are considered as increments in the equations which are linearized for each load. The program can account for both normal and tangential drag components and for discrete elements along the cable. The program has been extended to a small perturbation dynamic solution. Examples of static and dynamic problems are given in References 46 and 47, but since the program is considered proprietary, no listings are given.	46, 47
Henri O. Berteaux Woods Hole Oceanographic Institution Comm (617) 528-1400 K. Chhabra C. S. Draper Laboratory Cambridge, MA	2	Single-point moor with surface or subsurface buoy	yes	yes	yes	no	no	A. Cables are a series of finite elements. B. Wind and current forces on surface buoys are coplanar. C. Drag forces are based on current velocity at the mid-point of an element.	Two programs have been developed: (1) for the single-point mooring with a surface buoy and (2) for the same type of mooring with a subsurface buoy. Both programs use an initial-guess integration/iteration technique to fit the mooring system to the required depth of water and can handle any combination of discrete elements and point forces along the cable. For design, the subsurface program prints out where instrumentation should be placed to obtain a desired depth in a given current. Surface moorings may be slack or taut. Both programs consider the effects of normal and tangential drag and the elastic characteristics of the mooring line as established by actual tests. A listing of both programs is given in Reference 48.	43

continued

Table 1. Continued

Author Organization Telephone Number	Program Dimensionality	Mooring Type	Cable Material		Current Profile Variation With Depth		Program Validation	Assumptions	Remarks	Ref No
			Compound Cables	Extensible Cables	Magnitude	Direction				
Derek Bennet Bunker Ramo Westlake Village, CA Comm (213) 889-2211 Ext. 2857	2	Free-floating and single-point moored systems	–	–	yes	no	yes	A. Cables are a series of straight segments.	Two programs based on modifications of the Cuthill [39] program have been developed. One program examines the free floating cable-buoy weight system, and the other is for the bottom anchored single-point moored system. The programs "have shown good agreement with at-sea data." No program listings are available as the programs are proprietary.	49, 50
Swede Momson G.M. Research and Defense Labor Laboratory Goleta, CA Comm (805) 968-1011	2, 3	Single-point moor, Bi-moor, Tri-moor	yes	yes	yes	yes	no	Unknown.	Two computer programs have been developed. A two-dimensional one for single point moorings or drifting systems, accounts for discrete elements (instrumentation packages, etc.) along the cable, and considers both normal and tangential drag effects. The second program is based on the MIR and can be used for bi- and tri-mooring systems that are not internally redundant. The programs are proprietary, and no listings are available.	51

Table 2. Dynamic Programs

Author Organization Telephone Number	Program Dimensionality	Mooring Type	Solution Method	System Excitation	System Damping	Cable Properties	Status of Program	Remarks	Ref No
Professor H. C. Merchant University of Washington Seattle, WA Comm (206) 543-5628 M. C. Kelf Naval Torpedo Station Keyport, WA	2	Single-point, taut mooring.	Finite difference.	Steady current and first-order (Airy) wave forces.	Internal cable damping using a Voight model. Hydrodynamic damping of buoy and cable.	Cable is flexible and extensible. A polynomial defines the elastic properties.	The program is operational.	This program uses an explicit numerical solution technique to obtain buoy motion, cable tension and shape. The solution is obtained by approximating the buoy-system differential equations, using finite difference and suitable algorithms for the dependent variables. Program-solution-time to system-response-time for the CDC6400 computer is one-to-one. A program listing is given in Reference 53.	52, 53
N. T. Tsai General Dynamics Corporation Ocean Systems Programs San Diego, CA Comm (714) 279-7301 Ext. 3781	2	Slack or taut single-point mooring.	Method of bond graph.	Surface-wave and steady-current forces.	Hydrodynamic damping in the transverse direction.	Any cable for which power and energy variables can be formulated.	The program is operational and proprietary.	This program is a numerical model that treats a single-point mooring cable as a transmission line that has mass and is influenced by wave and current forces. The principle of this method is to formulate the physical problem in terms of power and energy variables and then proceed to the physical modeling by directly accounting for energy storage, supply, and dissipation effects based on fundamental physical considerations. Using the dynamic input at the buoy end of the cable, the variables associated with traveling waves in the cable can be calculated. Output consists of velocities and forces associated with the transverse waves in the cable. A description of the technique and example problems are given in Reference 54.	54, 55
H. T. Wang Naval Ship Research and Development Center Bethesda, MD Comm (301) 227-1410 Autovon 287-1410	2	Suspended cable systems.	Two-degree-of-freedom nonlinear model.	Surface-wave forces and nonuniform currents.	A Voight model for internal cable damping and hydrodynamic damping.	The cable is extensible and cable diameter decreases linearly with strain. Cable stretch is assumed to be uniform.	The program is operational and has shown good agreement with test data.	This program, named DM2DF, is for a free-floating or towed system and is presented for completeness. It assumes that the dynamic motion of free-floating or towed systems can be approximated by a two-degree-of-freedom nonlinear model. The two degrees of freedom are cable stretch and inclination. The model can be viewed as representing the cable by one straight segment divided into many subsegments so that the dynamic and drag characteristics of the system are closely modeled. Effects of normal and tangential drag are accounted for in the program as well as added mass for the cable. The equations of motion are derived by means of the Lagrange equations and are solved by the Kutta-Merson method. The program in its present form may be quite accurate for straight-cable systems under the action of coplanar surface and subsurface forces, but accuracy will begin to deteriorate as these restraints are violated. The author of Reference 56 feels that capabilities can be added to the program by representing the cable by several straight segments and by adding the third dimension. A program listing is not given in Reference 56.	56

continued

Table 2. Continued

Author Organization Telephone Number	Program Dimensionality	Mooring Type	Solution Method	System Excitation	System Damping	Cable Properties	Status of Program	Remarks	Ref No.
R. D. Taylor Tracor Incorporated Austin, TX Comm (512) 926-2800	1, quasi 2	Free-floating and single-point mooring systems.	Two methods used: (1) continuous model—closed form solution; (2) lumped parameter model—"tracked" perturbation analysis.	Surface wave forces and steady currents.	A Voight model for internal cable damping and nonlinear hydrodynamic damping.	For the lumped parameter model the cable is a series of segments with visco-elastic properties.	The programs are operational and proprietary.	These two programs have been developed to describe the dynamic displacement and tension in cable systems subject to surface wave forces and depth-varying drag forces. The lumped parameter model is quasi-two-dimensional (one-dimensional motion in a long two-dimensional track formed by the axis of the cable) and has shown fair agreement with experimental data, including the ability to predict when snap loads will occur. Solutions to the system of equations defining this model are obtained via numerical integration over time. The continuous model is one-dimensional, employs an equivalent linearization procedure to simulate payload (buoy) drag loading, and is used to predict the gross nature of a system's frequency response. A program listing for the initial version of the lumped parameter model is given in Reference 59.	57-59
D. J. Bennett Bunker Ramo Westlake Village, CA Comm (213) 889-2211 Ext. 2859	1	Free-floating and perhaps single-point mooring systems.	Lumped parameter-pseudolinear system	Surface wave forces.	Hydrodynamic damping.	Unknown.	The program is operational and proprietary.	This program uses a set of linear differential equations to describe the elements of a discretized cable-buoy system. Complex transfer functions are developed so that elements along the cable can be described with respect to harmonic wave excitation. The program has been shown to predict "actual dynamic behavior with acceptable error."	49, 50, 60
Professor R. F. Dominguez Texas A&M University College Station, TX Comm (713) 845-4515	2	Multicable systems.	Small perturbation-linearization method	Wind, wave, and current forces.	Structural and hydrodynamic damping must be linear, or must be accounted for, using energy concepts.	The cables are a series of straight segments that are rigid or elastic and have their mass lumped at nodes.	The program is operational and has been used for the two-dimensional analysis of multicable and suspended pipeline systems. Program listing availability is unknown.	This program is based on a discrete parameter approach to static and dynamic analysis which requires that first one must establish the static configuration of a mooring system and then examine the small amplitude dynamic oscillations of the mooring about its static equilibrium position. The equations of dynamic motion are linearized. Loading on the mooring may be distributed or concentrated and of a fixed or hydrodynamic nature. The primary limitations of this technique are the restriction to small amplitude analysis and the large computer storage requirements. The author of Reference 61 feel that three-dimensional dynamic analysis is possible using this technique. A flow chart for two-dimensional static and dynamic programs are given in Reference 61.	61
J. M. Gormally Now with TRW Systems Group Washington Operations Comm (703) 893-2000 R. Pringle Bell Telephone Laboratory Whippany, NJ	3	Large buoyant rigid systems.	Linearized equations of motion are numerically integrated.	Changes in current.	Damping is assumed to be a percentage of system moment of inertia.	Cables are elastic.	Program is operational and proprietary.	The linearized equations of motion are derived and integrated using the DEPAK computer package on the GE 635 computer. A program listing is not given in Reference 10.	10

continued

Table 2. Continued

Author Organization Telephone Number	Program Dimensionality	Mooring Type	Solution Method	System Excitation	System Damping	Cable Properties	Status of Program	Remarks	Ref No.
S. Bell Ocean Platform Systems General Electric Company Re-entry and Environmental System Division Philadelphia, PA Comm (215) 823-5362	2	Free-floating, slack or taut, single-point mooring systems.	Modified Newmark and Runge-Kutta numerical integration of equations of motion.	Wind, wave, and current forces.	Unknown.	Cables are elastic.	Programs are operational and proprietary.	Several programs for the dynamics of all or part of free-floating and moored systems have been written at GE. Emphasis has been placed on modeling the dynamics of surface buoys in heave, surge, and pitch, and in modeling subsurface moorings or suspended systems. When necessary, surface and subsurface models can be coupled to gain a total picture of the response of a system to the ocean environment. The programs consider inertia forces, added mass, form and friction drag, and variations in cable material.	14
B. W. Wilson Pasadena, CA Comm (213) 793-5710 D. H. Gorbaccio Hycon Manufacturing Company Monrovia, CA	2	Single-point, moored, surface surface vessel.	Two solution types: (1) finite difference/ method of characteristics, (2) pseudo-dynamic solution neglecting forces on and inertia of cables.	Steady wind and current forces plus wave forces as described by linear theory.	Hydrodynamic damping.	Cables are extensible and have most "real" cable properties.	Programs are operational and proprietary.	These programs have been developed for the dynamic analysis of single-point moored ships or other surface structures. Both programs assume the ship to be free of motion restraint other than against steady drift. With this assumption, the dynamic problem reduces to one of determining the effects of waves and current on the surface object and then applying these effects to the mooring cable along with steady drag to determine tensions and deflections as a function of time. The pseudodynamic solution is used for quick approximate answers while more complete solution is gained from the method-of-characteristics technique. According to the authors of Reference 62, computer time required per case is 15 minutes for the simplified program and 2 to 3 hours for the complete program when a CDC 3400 computer is used. No listing is given in the reference.	62
E. E. Zarnick M. J. Casarella* Catholic University of America Washington, D.C. *Comm (202) 635-5177	2	Multileg, moored, surface vessel with intermediate surface buoys in each leg.	Mooring forces due to drift displacement and unrestrained vessel motion are summed.	First- and second-order surface-wave forces and moments caused by waves.	Nonlinear viscous damping.	Cables are elastic.	Program is operational.	This program determines the dynamic behavior of multileg mooring systems for ships or other surface vessels in deep water. The assumptions are made that the moored ship's motions are essentially the same as that of an unrestrained ship and that ship pitch and heave motion can be related to cable tensions by catenary equations. For solution, the ship is given an initial displacement from the calm water position to balance drift caused by second-order wave forces and then is assumed to oscillate about this position. Cable tensions are the sum of those due to drift and oscillation. A program listing is given in Reference 64.	63, 64
C. L. Liu* J. A. Drelicharz Civil Engineering Laboratory Port Hueneme, CA *Comm (805) 982-4613 Autovon 360-4613	2	Taut single-point mooring.	Two solution types: (1) mechanical impedance/ transfer function; (2) pendulum analogy/ catenary equations.	Surface-wave and subsurface current forces.	Fluid-dynamic damping is a linear function of velocity.	(1) For the mechanical impedance solution, the cable is a series of rigid elements interconnected by springs; (2) for the pendulum analogy solution, the cable must be of constant mass per unit length and may be extensible.	Programs are operational.	These programs are both written in FORTRAN language and have been developed: (1) to estimate the line tension response of a surface buoy and taut cable to waves and (2) to estimate the oscillatory motions of a submerged buoy moored in an ocean current. The first solution uses the mechanical impedance approach to obtain a transfer function for the taut mooring system. The second solution uses the pendulum analogy and catenary equations	65

continued

Table 2. Continued

Author Organization Telephone Number	Program Dimensionality	Mooring Type	Solution Method	System Excitation	System Damping	Cable Properties	Status of Program	Remarks	Ref No
C. L. Liu (cont'd)								to determine cable tension, buoy equilibrium position, and frequency of oscillation of the submerged system. Many simplifying assumptions have been made in both solutions, but both programs are easy to use and are suitable for obtaining a quick "first-cut" engineering answer to these problems. A listing of both programs is given in Reference 65.	
W. Nerenstein* K. Smith Bendix Electrodynamics Division Sylmar, CA *Comm (213) 367-0111 Ext. 2454	2	Surface buoy and compliant cable at end of taut, submerged, single-point mooring.	Lumped parameter solution.	Surface-wave forces.	Hydrodynamic damping on surface buoy.	Cables are elastic.	Program is operational and proprietary.	This program simulates the dynamic behavior of the upper portion of a single-point mooring under the action of surface waves. Further details are not available.	43
M. Schreiber* H. H. Firuz Research and Development Division Lockheed Missile and Space Company Sunnyvale, CA *Comm (408) 742-0907	2	Single-point moorings.	Two solution types: (1) small perturbation linearization; (2) finite difference/ method of characteristics.	Surface-wave and ocean-current forces.	Unknown.	Unknown.	Programs are operational and proprietary.	The small perturbation program uses a static model to establish an equilibrium position for the system and then examines the dynamic response of the mooring about this position in the frequency domain. The second program is used to simulate the large displacement behavior of single-point mooring systems in the time domain. Efforts are being made to extend this program to the third dimension.	23, 24
A. Trampus Sperry Space Support Division for National Data Buoy Center National Oceanic and Atmospheric Administration Department of Commerce	2	Slack or taut single-point mooring.	Renormalization technique based on method of Godonov/small perturbation analysis.	Wave forces and coplanar steady-wind and current forces.	Linear hydrodynamic damping.	Cables are a series of elastic or inelastic segments.	Program is operational and listing is available.	This program is a new version of a program developed by Goodman, et al. (Reference 38) for the National Data Buoy Center. The program is applicable to surface-buoyed, single-point mooring systems and was developed to overcome the instabilities that are present in the original program when certain cases with long cables, high frequencies, and line attachments are considered. The new program is based on a staged renormalization of certain vectors in the solution process which precludes the presence of a singular matrix and the attendant instability. Successful trial runs using this technique have been made.	66
Professor R. Blumberg* C. D. Osborn American Science and Engineering Co. *Comm (713) 224-5454	2	Taut single-point mooring.	Integration/ iteration of equations for buoy motion.	Complex wave and steady current forces on the buoy.	Unknown.	Unknown.	Program is operational and proprietary.	This program attempts to simulate the dynamic behavior of a submerged near-surface buoy under the action of complex waves that have been synthesized by the linear superposition of several wave components. The program generates buoy-response curves for a given set of buoy and ocean parameters. Typical parameters which may be varied are buoy size and shape, drag and inertial coefficient, water and buoy depth, wave and current characteristics, and the initial position of the buoy.	67

continued

Table 2. Continued

Author Organization Telephone Number	Program Dimensionality	Mooring Type	Solution Method	System Excitation	System Damping	Cable Properties	Status of Program	Remarks	Ref No.
N. K. Chhabra Charles Stark Draper Laboratory Massachusetts Institute of Technology Cambridge, MA Comm (617) 258-1316	3	Taut single-point mooring.	Unknown.	Large-scale ocean current changes.	Unknown.	Unknown.	Program has been validated with data from a full-scale ocean test. Details of the program and its accuracy are being documented in a report.	The report documenting this program [68] is in preparation. Program details are not known.	68

Table 3. Mathematical Oscillator Models

Author	Model Type	Status of Model	Remarks	Ref No.
Prof. I. Dyer Massachusetts Institute of Technology Cambridge, MA Comm (617) 253-4330	Statistical Energy Analysis (SEA).	SEA has not been used in vortex-induced vibration problems, but appears to have potential in this area.	Because loads on mooring systems are usually spatially and temporally random in nature and because system damping and boundary conditions are seldom precisely known, a statistical approach to cable strumming has merit. SEA "is an attempt to model the structural system by an assemblage of modes whose mode shape, resonant frequency, damping, etc., are statistically determined." Energy of vibration is the primary dynamic variable in SEA and is used along with power-flow in the system to determine the characteristics of vibration. This technique has been successfully applied to various vibrating fluid and structural systems.	72-75
N. T. Tsai General Dynamics Corporation Convair Division San Diego, CA Comm (218) 279-7301	Method of bond graph.	Application of this technique has been outlined for moored cable systems.	The principle of this method is to formulate the physical problem in terms of power and energy variables and then proceed to the physical modeling directly by accounting for energy storage, supply and dissipation effects throughout the system based on fundamental physical considerations. Using this technique, it is theoretically possible to analyze complex cable systems for cable strumming. The analysis may include the effects of nonlinear damping and nonuniform spatial mass and tension distributions. However, some simplifying assumptions must be made regarding system environment interaction and energy storage and dissipation. An example problem is given in Reference 54, but no comparisons with experimental data are made.	54
Yasuharu Nakamura Kyushu University Fukuoka, Japan	Binary mechanical oscillator.	The equations used in the model have been formulated but have not been verified with experimental data.	Vortex excitation of a two-dimensional circular cylinder immersed in a uniform flow is treated as a self-excited oscillator of a linear binary system consisting of the cylinder and the flowing fluid. Birkhoff's oscillator model for the dead air region behind the cylinder is adopted as representing the fluid. The author has shown that for reasonable choices for the dimensions of the dead-air space, correct values for the Strouhal frequency and natural frequency of a stationary cylinder are obtained. For the oscillating cylinder, predicted behavior is generally unlike actual observed behavior.	76
Masaya Funakawa Technical Laboratory Kawasaki Heavy Industries Ikuta-ku, Kobe Japan	One-degree-of-freedom mechanical oscillator.	The equations used in the model have been formulated.	This model is similar to the model set forth by Nakamura and actually preceded the Nakamura model. Both models use the Birkoff oscillator for the dead-air region behind the cylinder. However, Funakawa's model considers the motion of the dead-air region to be a forced oscillation which is driven by the cylinder oscillation and the resulting flutter has one degree of freedom. Details of model performance are not known.	77

continued

Table 3. Continued

Author	Model Type	Status of Model	Remarks	Ref No.
D. Sheppard Charles Stark Draper Laboratory Massachusetts Institute of Technology Cambridge, MA Comm (617) 258-1316	Mechanical oscillator.	This model is still under development.	This model is basically a lumped parameter approach to the Karman Vortex Shedding phenomenon which uses the Birkhoff oscillator model. The model has not been completely refined and the performance characteristics are unknown; however, early comparisons with experimental data are encouraging.	78
Prof. Grampaola Di Silvio Padua University Padua, Italy	Fluid oscillator model.	Model is complete.	The model is based on the assumption that the downstream wake width is controlled by the position of the edge of the cylinder at the so-called vortex origin time which in turn is controlled by the motion of the cylinder. Results from this model do not agree well with experimental data unless adjustments are made in the solution process and in values for important parameters like structural damping.	79
H. Halle Argonne National Laboratory Argonne, Ill.	Fluid oscillator model.	Model is complete.	This model considers the fluid to be a linear one-degree-of-freedom oscillator driven by a sinusoidally varying lift force which remains in phase with cylinder displacement. The results obtained by this model are reported to show a lock-in frequency region and qualitative agreement with experimental values for phase angle between lift force and the cylinder motion, amplitude of motion, and frequency of motion when certain factors within the model are chosen match experimental values.	80
R. Hartlen Ontario Hydro Toronto, Canada I. G. Currie University of Toronto Toronto, Canada	Fluid oscillator model based on Van der Pol equation for the fluctuating lift on a cylinder.	Model is complete.	This model is based on a coupled pair of ordinary differential equations; one equation defines the dynamic motion of the cylinder while the second equation defines the oscillating lift on the cylinder using a Van der Pol equation. For stationary cylinders, mechanically oscillated cylinders, and cylinders forced to oscillate by vortex shedding in the lock-in range, this model produces good qualitative agreement with experimental data when the empirical constants in these equations are properly chosen.	81, 82
Prof. Sunio Kawamura Osaka City University Osaka, Japan	Linear oscillator model.	Model is complete.	This model utilizes an equation for a damped linear oscillator to represent the lift force on a cylinder. Experimental data is used to develop an expression for vibration frequency in terms of cylinder amplitude. The final equation is then solved for response amplitude and phase lag between cylinder and lift force. Insufficient data is given in the reference to assess model performance.	83

continued

Table 3. Continued

Author	Model Type	Status of Model	Remarks	Ref No.
R. A. Skop O. M. Griffin Naval Research Laboratory Washington, D. C.	Oscillator model based on a modified Van der Pol equation.	Model is complete.	This model, as in the model of Hartlen and Currie, is based on a Van der Pol equation for the oscillating lift force on a cylinder which is coupled to an equation for the dynamic motion of the cylinder. The Van der Pol equation is modified by inclusion of empirical parameters which help insure that the performance of the model matches experimental results. Since the value of some of the empirical parameters vary between experiments due to differences in experimental setup, relationships are developed between the empirical and physical parameters to made the model more general. Agreement between model predictions and experimental data for the "lock-in" range is quite good with particularly excellent agreement on the magnitude and location of the peak resonant amplitude of cylinder oscillation. Attempts are currently underway to expand the model to the cable strumming case.	84-86
Prof. W. D. Iwan Cal Institute of Technology Pasadena, CA Comm (213) 795-6811 Ext. 1144 R. Blevins Cal Institute of Technology	Oscillator model which includes a "hidden variable" to describe fluid dynamic effects.	Model is complete.	This model has been developed to describe the vortex-induced vibration of elastically supported cylinders. The model is based on a fluid oscillator equation coupled to an equation for the motion of a viscously damped cylinder. The model includes a "hidden variable" to describe the fluid dynamic effects of vortex shedding. Model parameters are determined by backfitting experimental results for stationary and forced cylinders. When model predicted and experimental results are compared for an elastically restrained cylinder, both show a distinct frequency entrainment. However, the model greatly underestimates the range of entrainment and produces values for the resonant frequency that are approximately 20% low. The model does show the correct interdependence between entrainment bandwidth and structural damping.	87

Table 4. Flow Field Models

Author	Model Type	Description of Bluff Body	Remarks	Ref No.
J. E. Fromm University of California F. H. Harlow Los Alamos Scientific Laboratory Los Alamos, NM	Finite difference solution to differential equations of motion for viscous incompressible flow past a plate.	Fixed flat plate normal to flow.	This is an early attempt to model the complex wake behind a body in impulsively started flow, using numerical approximations and a digital computer. Results are presented for flow parameters (critical Reynolds number, Strouhal number, drag coefficient, etc.) for flows ranging from R = 15 to R = 6,000. The model results show fair agreement with experimental results for the various parameters.	88
D. C. Thoman Bendix Corporation South Bend, IN A. A. Szewczyk University of Notre Dame South Bend, IN	Finite difference solution to differential equations of motion.	Stationary circular cylinder.	Numerical solutions for impulsively started time-dependent flow about a circular cylinder are presented for Reynolds numbers from 1 to 3×10^5. Comparison of model results with experimental data show reasonable correlation.	89
Prof. T. Sarpkaya Naval Postgraduate School Monterey, CA	Potential flow model for time-dependent flow.	Stationary circular cylinder.	A computer model based on potential flow theory is used to analyze the impulsively started steady flow about a circular cylinder. Comparison of calculated values for drag coefficient and circulation rates at R = 10,000, R = 30,000, and R = 60,000 with experimental results show excellent agreement. Work on the simulation of flow about circular cylinder using digital and analog techniques is continuing at the Naval Postgraduate School.	90, 91
Prof. A. D. K. Laird University of California Berkeley, CA	Potential flow model.	Stationary circular cylinder.	A computer model based on potential flow theory is presented which simulates the periodic vortex shedding from a cylinder in steady, uniform, crossflow. The model, in general terms, yields a fair picture of the flow pattern. A more advanced computer model for this type of flow is under development.	92, 93
S. K. Jordan The Analytic Sciences Corporation Reading, MA J. E. Fromm IBM Research Lab San Jose, CA	Finite difference solution to equations governing time-dependent, viscous, incompressible flow.	Stationary circular cylinder.	Computer model descriptions are presented for the oscillatory forces (drag, lift, and torque) imposed on a cylinder in two-dimensional crossflow at Reynolds numbers of 100, 400, and 1,000. When model predictions are compared with experimental results, an adequate description of flow at R = 100 and R = 400 is found. Model predictions at R = 1,000 are not entirely valid.	94

continued

Table 4. Continued

Author	Model Type	Description of Bluff Body	Remarks	Ref No.
R. R. Clements Engineering Department Cambridge University Cambridge, England	Discrete vortex approximation.	Stationary square based section.	An inviscid model for two-dimensional vortex shedding from a bluff-based body is presented. When model predictions are compared with experimental data, good agreement is noted for the shape of the shear layers during the vortex-shedding process, for the Strouhal number at $R = 1.4 \times 10^5$ and $R = 2.45 \times 10^5$ and for mean fluid particle velocity outside the wake. Agreement between oscillation amplitudes is not good although the general shape and trend of the calculated curves agree with the experimental results.	95
Y. N. Chen Research Laboratory for Vibration and Acoustics Sulyer Brothers Limited Winterthur, Switzerland	Ideal semi-infinite rectilinear approximation for the vortex street.	Stationary circular cylinder.	A mathematical model is presented for the vortex street formed behind a single circular cylinder in inviscid crossflow to $R = 10^7$. The model is used to predict the lift force exerted on the cylinder by the vortices and the swing movement of the near wake. Comparison of the model predictions with selected experimental data shows fair agreement for vortex formation, zone length, and maximum lift force.	96
J. S. Son Shell Development Co. Emeryville, CA T. J. Hanratty University of Illinois Urbana, IL	Finite difference solution for time-dependent equations of motion.	Stationary circular cylinder.	A mathematical model for steady flow around a circular cylinder at Reynolds numbers of 40, 200, and 500 is presented. Results for separation angle and drag coefficient at $R = 200$ and $R = 500$ were near steady-state values but were quite different. This indicates that steady flow at high Reynolds numbers may not be simulated by the model. Predicted values for viscous and pressure drag for steady-flow were found to be lower than for laboratory experiments where the wake is unsteady.	97
J. H. Gerrard University of Manchester Manchester, England	Finite difference solution to vorticity and continuity equations.	Stationary, square, rearward facing step.	A numerical model for the steady-state behavior of two-dimensional flow down a step at a Reynolds number of 100 is presented. The model is used to perform numerical experiments on the flow to gain insight into the relationship between Reynolds numbers, flow turbulence and low frequency fluctuations in the flow. Specific information about the finite difference technique used in the study is given in Reference 100; details of the numerical experiments are given in Reference 101.	98, 99

continued

Table 4. Continued

Author	Model Type	Description of Bluff Body	Remarks	Ref No.
J. Shioiri University of Tokyo Tokyo, Japan	Van der Pol oscillator representation of vortex shedding.	Stationary and forced oscillating cylinder.	A model for the synchronization phenomenon in vortex shedding is treated for two-dimensional inviscid flow. For the stationary case, calculated values for the Strouhal frequency are 20 to 30% higher than experimental values. For the forced oscillation case, good agreement is found between experimental and predicted values for minimum oscillation amplitude required for cylinder synchronization.	100
H. D. McLaugnlin B. H. Ugihara North American Rockwell Space Div. Seal Beach, CA Comm (213) 922-2111 Ext. 3949	Potential flow model with generalized Kutta condition to govern vorticity transport.	Stationary and flexibly restrained circular clyinders.	Numerical techniques for the analysis of two-dimensional separated flow about fixed and flexibly restrained, oscillating, circular cylinders have been developed. The analysis techniques are based on potential theory and have been programmed for solution on IBM 360-50 and IBM 360-65 computers. The program for flow about a fixed cylinder generated values for afterbody force and drag that are significantly higher than experimentally measured values at a Reynolds number of 500. The program for flow about a flexibly restrained, circular cylinder seems to be operational, based on the results from a single short run, but additional runs would be required before comparisons with experimental data are possible.	101, 102

continued

Table 5. Strumming Characteristics and Drag Coefficients for Some Bare and Faired Cables

(All data in this table is based on results obtained from ocean or water-channel tow tests.)

Cable or Fairing Type	Cable Description	Performance	Reynolds Number	Normal Drag Coefficient	Tangential Drag Coefficient	Ref No.
Bare wire rope	1/2 inch, 7 x 19.	This cable was observed to be vibrating at all tow speeds from 5 to 15 knots.	1.2×10^5	1.4	Approximately 2% of normal drag.	105
Hair cloth*	Fine hairs approximately 3 inches long resulting from helically wrapping frayed cloth around the cable.	Vibration amplitudes the same as bare rope at two speeds from 5 to 15 knots.	1.2×10^5	2.2	Probably quite high.	105
Thonged fairing I*	1/16-inch nylon thongs 8 inches long spaced at 6 per inch.	Vibration amplitudes negligible as compared to bare rope for tow speeds from 5 to 10 knots, and reduced for tow speeds from 10 to 25 knots.	1.2×10^5	2.6	Probably quite high.	105
Thonged fairing II*	Same as above except spaced at 4 per inch.	Same as above.	1.2×10^5	1.5	Probably quite high.	105
Thonged fairing with overhand knot*	Same as thonged fairing II but with overhand knot approximately 1 inch from end of thong.	Same as above.	1.2×10^5	1.5	Probably quite high.	105
Thonged fairing III*	1/16-inch nylon thongs 4 inches long spaced at 4 per inch.	Same as above.	1.2×10^5	1.3	Probably quite high.	105
Duck fairing*	Flexible canvas weathervane fairing approximately 6 inches wide.	Vibration amplitudes negligible for tow speeds of 5 to 10 knots, same as bare cable for speeds from 10 to 15 knots.	1.2×10^5	2.5	Probably quite high.	105
Bare wire rope	1/4 inch, 1 x 19.	Magnitude of vibration amplitude unknown.	6.3×10^4	1.33	Approximately 2% of normal drag.	105
Bare wire rope	5/16 inch, 7 x 19.	Same as above.	6.3×10^4	1.37	Same as above.	105
Bare wire rope	5/16 inch, 3 x 19.	Same as above.	6.3×10^4	1.22	Same as above.	105
Compacted bare wire rope	9/32 inch, 7 x 19.	Same as above.	6.3×10^4	1.45	Same as above.	105
Plastic-coated wire rope	5/16-inch OD.	Same as above.	6.3×10^4	1.22	Unknown.	105

continued

Table 5. Continued

Cable or Fairing Type	Cable Description	Performance	Reynolds Number	Normal Drag Coefficient	Tangential Drag Coefficient	Ref No.
Braided covering	Rough braid over stranded cable; OD = 11/32 inch.	Same as above.	6.3×10^4	1.46	Unknown.	105
Braided covering with haired fairing	Same as above but with 1/16 inch by 3-inch hairs spaced at approximately 6 per inch.	Same as above.	6.3×10^4	1.32	Probably quite high.	105
Double haired fairing	Same as above except two sets of hairs spaced at approximately 6 per inch.	Same as above	6.3×10^4	1.74	Same as above.	105
Ribbon fairing	0.015-inch-thick polyurethane film, 2 cable diameters wide, 6 diameters long, spaced at 1 to 3 diameters apart.	Optimum vibration suppression for least ribbon.	2.28×10^4 to 2.28×10^5	Unknown	Unknown.	106
Helical strake	1/4-inch cable wrapped around 1-inch tow cable with a pitch of approximately 10 inches. Direction of wrap reversed every 10 feet.	Vibration amplitude reduced by more than 50%.	High.	Unknown.	Unknown.	107

* Fairings applied to 1/2-inch, 7 x 19 cable.

DISTRIBUTION LIST

SNDL Code	No. of Activities	Total Copies	
–	1	12	Defense Documentation Center
FKAIC	1	10	Naval Facilities Engineering Command
FKNI	6	6	NAVFAC Engineering Field Divisions
FKN5	9	9	Public Works Centers
FA25	1	1	Public Works Center
–	9	9	RDT&E Liaison Officers at NAVFAC Engineering Field Divisions and Construction Battalion Centers
–	299	299	CEL Special Distribution List No. 11 for persons and activities interested in reports on Ocean Engineering

Civil Engineering Laboratory
A SURVEY OF TECHNIQUES FOR THE ANALYSIS AND DESIGN OF SUBMERGED MOORING SYSTEMS, by
N. D. Albertsen
TR-815 34 p. illus August 1974 Unclassified

1. Submerged moorings 2. Computer simulations I. YF53.535.004.01.005

Techniques useful for the design and analysis of moored cable systems are presented. Included are compilations of information describing computer programs for steady-state and dynamic analyses and methods for the analysis and suppression of cable strumming. It was found that the steady-state analysis of complex redundant structures and the dynamic analysis of simple structures are now possible. However, experimental data are required to validate the analysis procedures and related computer programs. In addition, it was found that procedures still need to be developed to reliably predict, describe, and suppress cable strumming in long cables exposed to oceanic conditions.

Civil Engineering Laboratory
A SURVEY OF TECHNIQUES FOR THE ANALYSIS AND DESIGN OF SUBMERGED MOORING SYSTEMS, by
N. D. Albertsen
TR-815 34 p. illus August 1974 Unclassified

1. Submerged moorings 2. Computer simulations I. YF53.535.004.01.005

Techniques useful for the design and analysis of moored cable systems are presented. Included are compilations of information describing computer programs for steady-state and dynamic analyses and methods for the analysis and suppression of cable strumming. It was found that the steady-state analysis of complex redundant structures and the dynamic analysis of simple structures are now possible. However, experimental data are required to validate the analysis procedures and related computer programs. In addition, it was found that procedures still need to be developed to reliably predict, describe, and suppress cable strumming in long cables exposed to oceanic conditions.

Civil Engineering Laboratory
A SURVEY OF TECHNIQUES FOR THE ANALYSIS AND DESIGN OF SUBMERGED MOORING SYSTEMS, by
N. D. Albertsen
TR-815 34 p. illus August 1974 Unclassified

1. Submerged moorings 2. Computer simulations I. YF53.535.004.01.005

Techniques useful for the design and analysis of moored cable systems are presented. Included are compilations of information describing computer programs for steady-state and dynamic analyses and methods for the analysis and suppression of cable strumming. It was found that the steady-state analysis of complex redundant structures and the dynamic analysis of simple structures are now possible. However, experimental data are required to validate the analysis procedures and related computer programs. In addition, it was found that procedures still need to be developed to reliably predict, describe, and suppress cable strumming in long cables exposed to oceanic conditions.

Civil Engineering Laboratory
A SURVEY OF TECHNIQUES FOR THE ANALYSIS AND DESIGN OF SUBMERGED MOORING SYSTEMS, by
N. D. Albertsen
TR-815 34 p. illus August 1974 Unclassified

1. Submerged moorings 2. Computer simulations I. YF53.535.004.01.005

Techniques useful for the design and analysis of moored cable systems are presented. Included are compilations of information describing computer programs for steady-state and dynamic analyses and methods for the analysis and suppression of cable strumming. It was found that the steady-state analysis of complex redundant structures and the dynamic analysis of simple structures are now possible. However, experimental data are required to validate the analysis procedures and related computer programs. In addition, it was found that procedures still need to be developed to reliably predict, describe, and suppress cable strumming in long cables exposed to oceanic conditions.

Civil Engineering Laboratory
A SURVEY OF TECHNIQUES FOR THE ANALYSIS AND DESIGN OF SUBMERGED MOORING SYSTEMS, by
N. D. Albertsen
TR-815 34 p. illus August 1974 Unclassified

1. Submerged moorings 2. Computer simulations I. YF53.535.004.01.005

Techniques useful for the design and analysis of moored cable systems are presented. Included are compilations of information describing computer programs for steady-state and dynamic analyses and methods for the analysis and suppression of cable strumming. It was found that the steady-state analysis of complex redundant structures and the dynamic analysis of simple structures are now possible. However, experimental data are required to validate the analysis procedures and related computer programs. In addition, it was found that procedures still need to be developed to reliably predict, describe, and suppress cable strumming in long cables exposed to oceanic conditions.

Civil Engineering Laboratory
A SURVEY OF TECHNIQUES FOR THE ANALYSIS AND DESIGN OF SUBMERGED MOORING SYSTEMS, by
N. D. Albertsen
TR-815 34 p. illus August 1974 Unclassified

1. Submerged moorings 2. Computer simulations I. YF53.535.004.01.005

Techniques useful for the design and analysis of moored cable systems are presented. Included are compilations of information describing computer programs for steady-state and dynamic analyses and methods for the analysis and suppression of cable strumming. It was found that the steady-state analysis of complex redundant structures and the dynamic analysis of simple structures are now possible. However, experimental data are required to validate the analysis procedures and related computer programs. In addition, it was found that procedures still need to be developed to reliably predict, describe, and suppress cable strumming in long cables exposed to oceanic conditions.

Civil Engineering Laboratory
A SURVEY OF TECHNIQUES FOR THE ANALYSIS AND DESIGN OF SUBMERGED MOORING SYSTEMS, by
N. D. Albertsen
TR-815 34 p. illus August 1974 Unclassified

1. Submerged moorings 2. Computer simulations I. YF53.535.004.01.005

Techniques useful for the design and analysis of moored cable systems are presented. Included are compilations of information describing computer programs for steady-state and dynamic analyses and methods for the analysis and suppression of cable strumming. It was found that the steady-state analysis of complex redundant structures and the dynamic analysis of simple structures are now possible. However, experimental data are required to validate the analysis procedures and related computer programs. In addition, it was found that procedures still need to be developed to reliably predict, describe, and suppress cable strumming in long cables exposed to oceanic conditions.

Civil Engineering Laboratory
A SURVEY OF TECHNIQUES FOR THE ANALYSIS AND DESIGN OF SUBMERGED MOORING SYSTEMS, by
N. D. Albertsen
TR-815 34 p. illus August 1974 Unclassified

1. Submerged moorings 2. Computer simulations I. YF53.535.004.01.005

Techniques useful for the design and analysis of moored cable systems are presented. Included are compilations of information describing computer programs for steady-state and dynamic analyses and methods for the analysis and suppression of cable strumming. It was found that the steady-state analysis of complex redundant structures and the dynamic analysis of simple structures are now possible. However, experimental data are required to validate the analysis procedures and related computer programs. In addition, it was found that procedures still need to be developed to reliably predict, describe, and suppress cable strumming in long cables exposed to oceanic conditions.