# A SURVEY OF PUBLICATIONS ON MECHANICAL CABLES AND CABLE SYSTEMS

by

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109

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## SUMMARY

A preliminary list of pertinent publications directly and indirectly related to various aspects of the steady-state and dynamical characteristics of mechanical cables and cable systems is presented. Brief abstracts are given for those investigations which are of a fundamental nature or have wide applicability to cable and towed body systems. An unannotated list of references on publications available in the open literature and unclassified technical reports that has been reviewed by the authors thus far is also included.

# TABLE OF CONTENTS

# PART I - INTRODUCTION

## 1. Purpose of the Study

Prior to the numerous research investigations presently initiated under this Contract, an intensive literature search was performed on the scientific and engineering investigations associated with the structural, hydromechanical, and acoustical aspects of cable systems. This report contains the preliminary results, thus far obtained from the survey.

An attempt was made to categorize and delineate those studies which appear to be of a fundamental nature and have wide applicability to cable and towed body systems. An annotated list of these publications is presented according to the alphabetical listing of authors. These studies are also cross-referenced by the key words of the subject matter. Finally, an extensive list of references is included which appears to be related to some aspect of cable systems.

This literature search is by no means complete nor does it indicate any definite pattern of investigation or conclusive results obtained in any specific area of investigation. However, it did indicate what particular aspects of cable related mechanical systems require detailed and fundamental studies.

This list of references should prove useful to investigators in the field of Ocean Engineering and other disciplines where the behavior of a cable-like element under a variety of excitations is of interest. It is hoped that this survey will stimulate further investigations and discussions on the subject.

## 2. Survey of Application Areas for Mechanical Cable Systems

Mechanical cables have long been used for towing, for remote control or for the supplying of communication or other service links between two vehicles. Operational requirements now imposed by both military and commercial interests suggest the future use of such mechanical linkages where tow vehicle speeds are higher, where separation distances between vehicles are greater, where an order of magnitude improvement in remote control is desired, where lightness in weight and smallness in size are demanded, and where reliability and simplicity in design and operation are mandatory. In addition new environmental factors are now to be considered such as high winds or stormy conditions in air-to-air and air-to-ground operations, and extremely deep depths in deep ocean search, inspection, recovery and salvage operations.

Examples of systems which are now being prepared to satisfy operational requirements and which demand efficient mechanical cable systems are as follows:

a. Bottom search and survey. A photographic and acoustic instrument package is towed several feet off the ocean floor by a mother ship by means of a cable which can also serve as a telemetric channel. Weight, strength and size of the cable are important design parameters. The spatial and temporal location of the cable are important in predicting where the instrumentation package will proceed following a maneuver by the surface ship. The instrument package even though towed can be both unpropelled and self-propelled. In the latter instance the package is called a "tethered" vehicle. Increased maneuverability of the tethered vehicle results from freedom to move about a given tow point, however additional problems in cable design result.

The deep ocean search and survey system will be called upon to conduct geological survey for research, as well as mineral recovery interests, to examine bottom areas prior to the salvage of lost satellites, missiles, ships and to examine bottom areas prior to the establishment of underground and underocean stations such as missile sites, acoustic listening posts or manned habitats.

b. Salvage recovery. Large objects can be recovered from the ocean floor by lifting-cables attached either to lifting buoys which are inflated or to surface ships which provide lift forces via a mechanical power hoist. The dynamic behavior of the cable during initial breakout of the object from its immersion in the ocean floor sediments and during the subsequent passage to the surface is directly related to practical problems such as cable breakage, cable wear and cable corrosion. The lifting cable is in effect an anisotropic solid subjected to longitudinal bending and torsional vibrations where peak dynamic stresses and strains are difficult to predict. The problem is further complicated by the motion of the lifting ship or buoy.

Small objects may also be the concern of a cable-type recovery system. For example the H-bomb lost off Palomares, Spain was recovered by an unmanned tethered vehicle, CURV, operated by the Naval Ordnance Test Station, Pasadena (California). Fear of entangling a manned vehicle in the bomb parachute-shroud dictated the use of an unmanned cable-controlled recovery vehicle.

c. High speed sensor towing. To take advantage of radio communication while submerged, a radio antenna can be towed on the surface or just below the surface by a submarine or other deep vehicle.

To take advantage of sonar operations away from sea state and below a thermocline or even in the deep sound channel a sonar sensor can be towed from a surface ship. Both concepts involve high tow speeds if the tow vehicle is to take full advantage of its inherent high speed of maneuverability or speed of advance. The dynamic behavior of both cable and tow vehicle under these conditions relates to the design parameters of the cable, location of the sensor relative to the towship and stability of the towed vehicle.

d. Helicopter Recovery. Towing and lifting of an object from either the ground or the sea by a helicopter is common practice in military and civilian operations. The particular problem of lifting an object submerged or floating in a confused sea warrants special consideration because of the two layered fluid media involved. The design of a cable for maximum dynamic strength, minimum weight and low drag will also be required. Other cable problems such as the sea moor of oceanographic ships or monitor buoys, the placement of objects on the ocean floor, the air-to-air recovery of a manned space craft returning from outer space, the in-flight tow of airborne vehicles, and the possible tow of submerged objects by airborne vehicles are also of great technological importance.

# PART II

## ANNOTATED LIST OF PERTINENT REFERENCES

Abramson, H. Norma

"Flexural Waves in Elastic Beams of Circular Cross Section"
J. Acoustical Society of America, Vol. 29, No. 1, pp. 42-46, Jan 1957.

Flexural Vibrations of a solid circular cylinder are investigated using the equations of elasticity. The primary purpose of the paper is to gain additional insight into the physical phenomena involved in the flexural response of beams to impulsive loads.

Achenbach, J. D. and G. Herrmann

"Dispersion of Free Harmonic Waves in Fiber-Reinforced Composites"
Technical Report No. 67-3 (Northwestern University) June 1967.

Displacement equations of motion are obtained for fiber reinforced composites. Propagation of plane harmonic waves is studied. Plane transverse waves propagating in the direction of the fibers are dispersive and dispersion curves are shown.

Anad, G. V.

"Nonlinear Resonance in Stretched Strings with Viscous Damping"
Journal of the Acoustical Society of America, Vol. 40, No. 6, pp. 1517-1528, Dec. 1966.

A careful study of amplitude jumps and nonplanar oscillations, which are characteristic features of nonlinear resonance in stretched strings is presented. Damping is taken into account. Expressions for the resonance frequency and amplitude, and the frequencies and amplitudes at which the jump occurs, have been obtained. It is shown that the resonance frequency is not a constant of the system but increases with the driving force.

Author Unknown

"Notes on the Resistance of Rods, Cables and Ropes in Water"
DTMB Report R-31, Dec. 1940.

These notes discuss and review experiments on tow lines (resistance to towing and power required to tow manila rope, iron wire, insulated conductor, mine sweeping gear, etc.).

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Author Unknown

"Tension in a Cable Towing a Heavy Weight Through a Fluid"
DTMB, Report R-33, March 1941.

This short report presents computations of tension in a 1/16-inch diam. stranded cable, 600 ft. long, towing a 30 lb. weight at speeds from 5 to 12 knots.

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Ballou, Charles L.

"Investigation of the Wake Behind a Cylinder at Coincidence of a Natural Frequency of Vibration of the Cylinder and the Vortex Shedding Frequency"
Report No. 76028-2; Contract NONR 3963(25); Acoustics and Vibrations Laboratory, Massachussets Institute of Technology, May 1967.

Theory for aeolian tone intensity created by rigid circular cylinders has been found to agree quite well with experimental results. This investigation is to experimentally explore the wake of a cylinder shedding vortices at a frequency that is equal to one of the natural vibrational frequencies of the cylinder. Investigation was carried out in the following areas:

1. lateral special correlation of vortex shedding.

2. distance behind cylinder and value of RMS velocity at assumed position where vortices start to "roll up".
3. observation of the phase between velocity signals at two points along a cylinder.

The lateral spatial correlation of vortex shedding, the distance behind the cylinder, and the value of RMS velocity at assumed position where the vortices start to "roll up", were found not to deviate from the normal trend with respect to Reynolds number when coincidence of the two frequencies occur.

In observing the phase between velocity signals at two points along the cylinder the signals did not maintain a constant phase relationship, but were continuously shifting in phase in no particular pattern.

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Beebe, K. E.

"Mooring Cable Forces Caused by Wave Action on Floating Structures" College of Engineering, University of California (Berkeley) Series 3 - Issue 366, June 1954.

The report presents experimental data on forces on mooring cables caused by wave action on floating structures. Quantitative measurements were made of the horizontal cable force exerted by the mooring cable on a force meter at the bottom, the surface time history of the waves transmitted past the structure, and the surface time history of the waves without the model in the water.

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Bernstein B., D. A. Hall and H. M. Trent

"On the Dynamics of a Bull Whip" J. of the Acoustical Society of America, Vol. 30, No. 12, Dec. 1958.

The production of a cracking sound by a bull whip is analyzed. It is shown that the tip of the whip exceeds the speed of sound and generates shock waves. This is very successfully done by means of photography. A mathematical discussion is also given, it is explained how the free end of the whip achieves a high velocity while the end held in the hand moves rather slowly.

The equations governing the motion of the whip are

$$\frac{\partial}{\partial s}\left(T\frac{\partial x}{\partial s}\right) = \rho\frac{\partial^2 x}{\partial t^2} \tag{1}$$

$$\frac{\partial}{\partial s}\left(T\frac{\partial y}{\partial s}\right) = \rho\frac{\partial^2 y}{\partial t^2} \tag{2}$$

$$\left(\frac{\partial x}{\partial s}\right)^2 + \left(\frac{\partial y}{\partial s}\right)^2 = 1 \tag{3}$$

Eq.(3) expresses inextensibility.

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Berteaux, H. O.

"Surface Moorings, Review of Performance"
Reference No. 68-20, Woods Hole, Mass., March 1968.

A brief history of moorings is presented. The possible types of failures are reviewed. A theory which could explain the failure of the wire ropes is presented. This report is quite interesting from a materials viewpoint.

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Berteaux, H. O., E. A. Capadona, R. Mitchel and R. L. Morey

"Experimental Evidence on the Modes and Probable Causes of a Deep-Sea Buoy Mooring Line Failure" Transactions of the 4th Annual MTS Conference, Washington, D. C. (8-10 July 1968)

This paper presents the case history of an instrumented buoy system found adrift and recovered from the Atlantic Ocean. It describes the mechanical and metallurgical tests performed on the mooring line in an attempt to establish the modes of failure of this typical deep-sea mooring. Present (1968) engineering efforts accomplished at or with the Woods Hole Oceanographic Institution are outlined.

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Bhuta, Pravin G. and John P. Jones

"On Axial Vibrations of a Whirling Bar"
Journal of the Acoustical Society of America, Vol. 35, No. 2, Feb. 1963.

Axial vibrations of whirling bars are studied using Lagrangian coordinates. Whirling lowers the natural frequencies, in general. When Lagrangian Coordinates are used an interesting result is obtained: as the angular velocity of the bar reaches a certain critical value, a solution does not exist. This phenomenon is called "static resonance".

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Billing

"Oscillations Excited in the Cable of a Bomb Towed Behind an Aircraft"
ZWB FB 1772; Report of the Aerodynamics Research Institute, Gottingen, Germany, 1943. Technical Translation No. TT-88; National Research Council of Canada, Ottawa, May 1949.

Very often, when a bomb is towed behind an aircraft at the end of a rather long cable, both cable and bomb oscillate violently. The report shows that small deflections, such as those due to gusts, travel along the cable as waves, and that they increase exponentially due to the incident flow. Thus, disturbances which are originally small can prevent the steady flight of the bomb. Theoretical results are compared with experimental evidence.

The Boeing Company, Aerospace Group

"Tests and Investigations of a High Speed Towed Sonar Cable"
Final Report - D2-133006-1 prepared for the U.S. Navy Electronics Lab.
June 1966.

The present report is a continuation of Ref. (1)*. In that report the mechanical and hydrodynamic feasibility of a low-drag, faired cable for towing submerged bodies at high speeds was demonstrated. Additional research and development was recommended in order to achieve an optimum production cable. Some of the problems encountered were lower cable strength, higher drag and higher cable noise level. This study pursues in part the recommendations set above. Specific areas of interest are: 1) mechanical testing of various cable components and cable samples to determine torsional rigidities and centers of rotation, 2) mechanical testing of several cable samples to determine their centers of tension, 3) mechanical testing of a partially segmented, polypropylene faired, fiberglass tension member towing cable to determine its ability to withstand simulated drum winding; 4) manufacture several hydrodynamic models using full scale cable polypropylene fairing to permit determination of basic coefficients of performance with slotted and unslotted fairings by NEL and Hydronautics, (Laurel, Md.) and 5) performance of a cable stability and flutter investigation using a passive analog computer.

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*(1) D2-23504, Final Report, High Speed Towing Cable Development, CONFIDENTIAL, July 31, 1964.

Brennan, J. N.

"Large Amplitude Vibrations of Rods and Tubes at Audio Frequencies"
J. of the Acoustical Society of America, Vol. 25, No. 4, pp. 610-616
July 1953.

This paper describes an apparatus designed to determine accurately the velocity of sound and the log decrement in rods and tubes vibrating in a longitudinal resonant mode. Large strain amplitudes may be used in the frequency range up to 10 kc. One novel feature of the apparatus is the use of tuned resonant supports tilted with respect to the specimen; the tilting minimizes the tendency to chatter due to the Poisson effect. The supports are driven at their resonant frequency.

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Britton, W. G. B. and G. O. Langley

"Stress Pulse Dispersion in Curved Mechanical Waveguides"
Journal of Sound and Vibration, Vol. 7, No. 3, pp. 417-430, 1968.

The dispersion of elastic waves in Cylindrical rods has been studied extensively. Propagation in a rod where the axis is a curve has received little theoretical attention and even less experimentally. The present paper is concerned with dispersion in curved mechanical waveguides. The case of propagation in a rod of circular cross-section where the central elastic line is a helix is investigated using a wide band, short-duration pulse technique. The experimental results were interpreted using Kelvin's principle of stationary phase. Some theoretical dispersion curves have been computed for circular rings and helical springs using available theories.

Brown, Denny F.

"The development and Evaluation of the TMB Cable Tension and Footage Indication System" DTMB Report 1701, January 1963.

The present report describes the operation and evaluates a portable system designed to measure tension and footage payout remotely and continuously on a stationary or moving cable. During tests of the system, accurate readings were obtained for static cable tensions up to 70,000 lbs., moving cable tensions up to 45,000 lbs. and cable payout speeds up to 70 ft/min. The system was designed specifically for use with 1.25 inch diameter cable for the TOTO II moor, use on cables of smaller diameter is possible. The sheave-groove size precludes use on cables of larger diameter.

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Busby, R. F., L. M. Hunt and W. Rainnie

"Hazards of the Deep" Ocean Industry, Vol. 3, No. 7, July 1968.

Two kinds of hazards are considered: 1) man-made hazards (cables, wrecks, etc.) and 2) natural hazards (see state, currents, topography, etc.). The first hazard mentioned are cables. Submarine cables may be used for power, communication, mooring or a combination of these functions. Cables may also exist as lost or discarded material.

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Champion, Albert R.

"A Streamlined Cable Depressor" University of California, Division of War Research, UCDWR No. M68, May 25, 1943.

This report consists of two parts, the first with a simplified calculation of forces acting on the cable system when a submerged object is towed.

The second with the design of a depressor. This investigation was related to the research on towed hydrophones.

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Chubachi, Tatsuo

"Vibration of String and Beam with Time-Dependent Lengths" Proc. of the 1st Japanese National Congress for Applied Mech., 1951, pp. 605-610.

In the case a string it is assumed that the elements of the string neither elongate nor translate in the direction of length; the outward velocity of the two ends is $V_1$ and $V_2$, respectively. Let the length of string be $\ell_o$ and $\ell$, at t=0 and t respectively. We then have

$$\ell = \ell_o + Ct = C\tau$$

where

$$C = V_1 + V_2 \; ; \quad \tau = t + \ell_o/C$$

The equation of motion of the string is the well known one dimensional wave equation.

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Clark, S. K.

"Torsional Wave Propagation in Hollow Cylindrical Bars" Journal of the Acoustical Society of America, Vol. 28, No. 6, pp. 1163-1165; Nov. 1956.

The objective of this paper is to present numerical information on the velocity of torsion waves in hollow cylindrical tubes. Davies and Owen* and McSkimm** considered the torsional problem for solid cylindrical bars.

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* R. M. Davies and J. D. Owen, Appl. Mech. Rev. 4, Review 9 (1951)

** J. McSkimm, J. Acoust. Soc. Am., Vol. 24, pp. 355-365 (1952)

Cuthill, Elizabeth H.

"A Fortran Program for the Calculation of the Equilibrium Configuration of a Flexible Cable in a Uniform Stream" DTMB Report No. 1806, March 1964.

A computer program is described for calculating the equilibrium configuration of a flexible cable in a uniform stream in a plane determined by the direction of motion and by the direction of the force of gravity. To calculate the loading on the cable equations derived by Pode* and Whicker are used.**

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* Pode, L. "Tables for Computing the Equilibrium Configuration of a Flexible Cable in a Uniform Stream" DTMB Report 687 (June 1951) and Supplement (Sept. 1955)

** Whicker, L. F. "The oscillatory Motion of Cable-Towed Bodies" University of California Institute of Engineering Research Report (May 1957)

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Dale, J. R.

"A Force Balance Analog for Determining Characteristics of Ocean Cable Systems" Report NADC-AE-6517, 16 Nov. 1965.

A force balance analog is a new tool for solving any flexible cable system problem that can be instantaneously represented by a balance of static forces. The analog is capable of reproducing computer program solutions to within ±5 percent for cable tensions and physical geometry. The force balance analog is simply a vertical board display of the balance of a simulated nonconcurrent, coplanar force system with reduced force and geometric scales. Assumptions are developed for the analog based on a classical static analysis of a free rigid body system. Design features of the analog are described, and design criteria is presented for choosing realistic vertical ocean velocity profiles simulating surface and abyssal circulations, and cable parameters.

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Dale, J. R. and H. R. Menzel

"Flow Induced Oscillations of Hydrophone Cables" 23rd Navy Symposium on Underwater Acoustics, 30 Nov. - 2 Dec. 1965, pp. 411-423.

A study of flow effects on hydrophone systems and associated acoustic signals is outlined with the objective of providing criteria for design and evaluation.

The transverse oscillatory motion modes of hydrophone cables are predicted by vibrating string theory where the forced excitations are the oscillatory lift and drag forces. Experimental verification within the Reynolds number range 500 to 5,000 was found from the spectrum analysis of dynamic tension measurements, and motion photography.

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Dale, J.

"Hydrodynamic Analysis of the AN/SSQ-41 Sonobuoy Hydrophone Suspension System" Report NADC-AE-6636, January 1967.

The present report discusses the underwater motion modes of the AN/SSQ-41M Sonobuoy. Several interesting conclusions and recommendations are stated. A simple spring-mass-dashpot model was used to study the effects of surface wave-periodic motion.

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Dale, J. R. and R. A. Holler

"Fluid Excitation Criteria for a Cylinder Oscillating in a Steady Flow" TM 7-67, Naval Air Development Center, September 1967.

Flow-induced excitation of flexible cables that suspend hydrophones to various ocean depths is known to cause spurious hydrophone signals. These signals frequently mask the target. A fundamental understanding of the flow-induced excitation phenomenon will not only help solve the hydrophone cable problem; it will provide the basis for understanding many types of flow-excitation. Typical examples include vibrating (strumming) flexible cables, fishtailing rigid cylinders, singing propellers, and vibrating elastic structures.

A tractable model to study flow-induced excitation is the circular cylinder oscillating transversely to a flowing medium. The cylinder can either be oscillated externally, in which case the amplitude and frequency can be controlled, or it can be part of a simple elastic system used diagnostically to study the fluid effects.

The present study has two objectives:

1. To formulate the fluid-excitation criteria for an oscillating cylinder in a flowing fluid that will form a basis for interpretation of flow-induced excitation.

2. To provide direction for future studies of a basic nature aimed to further refine these criteria.

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Dale, J. R. and R. A. Holler

"Spurious Signals from Air Launched Sonar Systems" 3rd Marine Systems and ASW Meeting, San Diego, California, April 29 - May 1, 1968, Paper No. 68-228.

Spurious sonar signals from ASW equipment in the dynamic ocean environment are discussed. Emphasis is placed on the hydromechanical flow-excitation phenomenon that plagues motion-sensitive equipment. Standing wave cable vibrations (cable strumming) and tone effects are shown to be characteristics of flexible cables in ocean currents. The magnitude of the water drag on a cable has been found to depend on cable strumming Drag coefficients increase as much as 35%. Results of recent studies show why the energy exchange to cylindrical shapes (i.e., flexible cables, hydrophones, and other components) is enhanced and limited by the transverse flow-excited vibrations. Engineering criteria are presented for effective designs to negate the causes of spurious signals from air launched sonar systems.

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Dale, J. R., M. M. McCandless and R. A. Holler

"Dynamic Response of a Suspended Hydrophone to Wave and Flow Effects"
ASME Paper 68-FE-39; presented at the Fluids Engineering Conference,
Philadelphia, Pa., May 6-9, 1968.

The dynamic response to simulated wave motions and horizontal water flows of a scaled model of a sonobuoy hydrophone suspension is studied. Circular and elliptical wave motions with periods from 2 to 15 sec. are considered and flow fields of 0.6 and 1.0 knot are used. The sonobuoy models were scaled from prototypes having cables 50 and 100 ft. long to a model of 9 ft. A useful photographic technique is discussed. The motion of the hydrophone suspension is probable cause of spurious hydrophone signals.

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Dale, J. R., R. A. Holler and G. Goss

"Flow Excited Underwater Cable Vibrations" Naval Air Development Center,
Johnsville, Warminster, Pa., 1968 (Naval Research Reviews, Vol. XXI,
No. 7, July 1968)

A review of flow-excited vibrations of cables is presented. These are problems of interest to the Navy in many areas. Some cable investigations at NADC were motivated by the problem of false or spurious signals from air-launched sonar systems. These systems suspend a hydrophone to a predetermined water depth by means of flexible cables. In the case of a cable which is excited to standing wave vibrations by vortex shedding, the amplitude of vibration varies from a maximum at the antinode to a minimum at the mode. This amplitude has an important effect on the correlation of vortex shedding along the cable. This dependence of the vortex shedding on the amplitude of vibration has been determined at NADC.

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Dong, R. G. and R. F. Steidel, Jr.

"Contact Stress in Stranded Cable" Experimental Mechanics, May 1965, pp. 142-147.

This paper deals with 1) the determination of the contact-stress condition between layers of strands within a cable by means of photoelasticity, 2) a design criterion for an optimum suspension clamp.

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Drucker, D. C. and H. Tachau

"A New Design Criterion for Wire Rope" Journal of Applied Mechanics, March 1945, pp. A-33 - A-37.

This paper shows that a dimensionless bearing-pressure parameter $B=2T/U\cdot d\cdot D$ (where T: tension in wire rope, U: ultimate tensile strength, d: diameter of wire rope and D: pitch diameter of sheave) is of prime importance in the proper choice of wire rope.

Eames, M.

"The Configuration of a Cable Towing a Heavy Submerged Body from a Surface Vessel" Report PHX-103 Naval Research Establishment - Dartmouth, N. S., November 1956.

The report discusses various laws of hydrodynamic force assumed for cables and fairings, illustrating the doubt which remains as to the true law for a faired cable. For a particular law of force a method is derived, amenable to direct integration, which accounts for the effect of cable weight, and it is shown that this may reasonably be applied to more general cable laws. A procedure for calculation minimizing arithmetical work is proposed and tables and curves for general use are presented. A comparison of the results of full scale trials with calculations demonstrates that the technique proposed is quite adequate.

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Eames, Michael C.

"Steady-State Theory of Towing Cables" Defense Res. Establishment Atlantic 67/5, 1967.

The advent of low-drag faired cable has greatly increased the scope of devices towed deep behind a ship, but improved design techniques are necessary to exploit the towing depths and speed now feasible.
The author points out that considerable amount of experimental work is needed to verify the assumptions used in the determination of loading functions of practical faired cables. An approximate determination of the cable configuration in a turn is given. The approach is valid when the lateral displacement of the body is small compared with the turning radius of the ship.

Edwards, A. T. and J. M. Boyd

"Field Observations of Mechanical Oscillations of Overhead Conductors - Terrain and Other Effects Conductor Vibration and Galloping Symposium, IEEE Summer Power Meeting, Chicago, Illinois, June 1968.

Field measurements on overhead conductors are presented to demonstrate the significant effects of terrain and ground clearance on conductor vibration and bundle sub-conductor oscillations. The paper shows that damping systems considered adequate for lines in typical rolling or treed terrain are not necessarily suitable for similar lines in very exposed areas. The effects of suspension clamp geometry on conductor fatigue are also discussed.

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Edwards, A. T. and A. E. Livingston

"Self Damping Conductors for the Control of Vibration and Galloping of Transmission Lines" IEEE Symposium on Conductor Vibration and Galloping, Chicago, June 25, 1968.

The present study shows the effectiveness of the self damping conductor to solve the aeolian vibration problem. The possibility of controlling galloping and other low frequency oscillations is discussed. Additional research is needed.

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Elmendorf, C. H. and Bruce C. Heezen

"Oceanographic Information for Engineering Submarine Cable Systems" Bell Technical Journal, Vol. XXXVI, September 1957, No. 5.

This paper deals with specific problems of immediate interest in the technology of submarine cable systems. Existing knowledge is discussed. Specific routes are suggested. Many cable breaks occur where the cables pass over sea mounts, canyons and areas susceptible to turbidity currents and an effort must be made to avoid such hazards. Topographic studies form the basis for both initial route selection planning and for a preliminary description of the selected route.

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Esrig, M. I. and D. J. Henkel

"The Use of Electrokinetics in the Raising of Submerged Partially Buried Metallic Objects" Cornell University, Dept. of Geotechnical Engineering, Report No. 7, June 1968.

The forces required to remove a metallic object buried in a soil mass are shown to be reduced significantly when direct current is passed between the object and a nearby, buried electrode. The object to be removed must be the negative electrode (cathode).
The forces that must be overcome to remove a buried object are shown to be adhesion on the sides and suction on the base. The electro-osmotic transport of water to the surface of the object and the production of gas due to electrolysis are shown to reduce both the adhesion and the base suction. During the model studies, the application of direct current permitted objects to be removed with net upward forces of between 5 and 45 per cent of the static pull-out forces (no electrical power).
A theory is presented to suggest the rate at which water pressure develops at the face of a buried object used as a negative electrode. This water pressure reduces the side frictional forces (adhesion) and the experiments suggest that the rate of pressure development is predictable, within engineering limits.

Etkin, B., G. K. Korbacher and R. T. Keefe

"Acoustic Radiation from a Stationary Cylinder in a Fluid Stream (Aeolian Tones)" J. of the Acoustical Soceity of America, Vol. 29, No. 1, Jan 1967.

The equation for the radiated sound associated with body forces in a fluid is applied to the flow past a circular cylinder. The sound field is found to be related to the oscillating lift and drag forces which act on the cylinder. Quantitative predictions are made of the field direction and intensity. One of the conclusions of the authors is the fact that the sound spectrum consists of one strong peak at the fundamental frequency, a weaker peak at double that frequency and wide band noise at frequencies higher than the fundamental.

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Fage, A. and V. M. Falkner

"Further Experiments on the Flow Around a Circular Cylinder" Reports and Memoranda No. 1369, (Ae 493) February 1931, Great Britain

The intensity of friction on the surfaces of two cylinders of 2.93 in. and 5.89 in. respectively have been determined from measurements of velocities taken at distances of 0.0025 in. from the surface with small surface tubes. The frictional distribution measured on the 5.89 in. cylinder is in fair agreement with the theoretical prediction.

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Ferguson, N. and G. V. Parkinson

"Surface and Wake Flow Phenomena of the Vortex-Excited Oscillation of a Circular Cylinder" Journal of Engineering for Industry, Transactions of the ASME, pp. 1-8, 1967.

Using an original design of acoustic-level pressure transducer, measurements were made of fluctuating pressures on the surface and in the wake of a circular cylinder at rest and in vortex-excited oscillation at sub critical Reynolds numbers. Frequency, amplitude, and phase, where relevant, of the cylinder oscillation were also measured, and some effects of cylinder oscillation on the organized wake geometry were observed. The new results are compared with relevant existing information for the stationary cylinder, and with the few measurements previously available for the oscillating cylinder, and some analysis is made.

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Fitch, Arthus H.

"Observation of Elastic-Pulse Propagation in Axially Symmetric and Nonaxially Symmetric Longitudinal Modes of Hollow Cylinders" Journal Acoustical Society of America.

Experimental measurements of group velocity in both axially symmetric and nonaxially symmetric longitudinal modes of hollow cylinders are presented and compared with theoretical values. In the case of solid cylinders experimental work was done by Davies.*

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*Davies, R. M., Trans. Royal Soc. (London) Vol. 240, p. 375 (1948)

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Fletcher, Harvey

"Normal Vibration Frequencies of a Stiff Piano String" Journal of the Acoustical Society of America, Vol. 36, No. 1, pp. 203-209, 1964.

Vibrations of strings having a solid-steel core upon which are wrapped one or two copper windings (the bass strings of most pianos are made this way). Two boundary conditions are considered: a) pinned at both ends and b) clamped at both ends. Analytical and experimental results are obtained and compared. The governing partial differential equation is:

$$T\left(\frac{\partial^2 y}{\partial x^2}\right) - QSK^2\left(\frac{\partial^4 y}{\partial x^4}\right) = \rho S\left(\frac{\partial^2 y}{\partial t^2}\right)$$

where T: tension; Q: modulus of elasticity; S: cross section area; K: radius of gyration and $\rho$ : density of the string material.

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Fofonoff, N. P. and J. Garrett

"Mooring Motion" Reference 68-31; Woods Hole Oceanographic Institution, Woods Hole, Mass., May 1968.

The authors define mooring motion as the change in the equilibrium position of a moored buoy in response to a change in the direction and speed of the current flowing past the mooring. The motion has maximum amplitude near the surface and decreases to zero at the bottom. Current measurements are made relative to the mooring so that mooring motion is present as an extraneous signal in the measurements. A simple mathematical model is used. Since the major contribution to the horizontal drag on a mooring occurs in the upper 10 to 20% of the water column where currents are usually strongest, it is assumed as a first approximation that the horizontal drag can be represented by a concentrated force acting on the mooring float itself.

The drag force F acting on the cross section A of the mooring is estimated by the equation:

$$F = 1/2\, \rho\, C_D \cdot A \cdot V^2$$

Frisch, Harold P.

"The Dynamic Characteristics of Satellites Having Long Elastic Members" NASA, TN D-4576, August 1968.

The paper presents equations applicable to any satellite having long elastic members that can be modeled as a symmetric double-beam system. The equations developed in dimensionless form and the results given provide sufficient information to allow for a straightforward determination of the natural frequencies of the system.

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Frohrib, D. A. and R. Plunkett

"The Free Vibrations of Stiffened Drill Strings with Static Curvature" Journal of Eng. for Industry, Vol. 89, Series B, February 1967.

The natural frequencies of lateral vibrations of a long drill string in static tension under its own weight are primarily the same of those of the equivalent catenary. The effect of bending stiffness and lateral deflection of the bottom end are taken into account. General equations are derived; solutions are obtained in the form of an asymptotic expansion with the bending stiffness as a parameter. The first three natural frequencies are computed for a wide range of horizontal tension and bending stiffness. Zero vertical static force at the bottom is assumed. The paper contains several important references.

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Frost, M. A. and J. C. Wilhoit, Jr.

"Analysis of the Motion of Deep-Water Drill Strings - Part 2: Forced Rolling Motion" Journal of Eng. for Industry, ASME, Vol. 87, Series B, May 1967.

Gibbons, T. and C. O. Walton

"Evaluation of Two Methods for Predicting Tow Line Tensions and Configurations of a Towed Body System Using Bare Cable" David Taylor Model Basin, Report 2313, December 1966.

Two alternative methods for predicting steady-state configurations and towline tensions are evaluated by comparing predicted data with experimental data. Between the two methods, Method 1 is shown to provide better overall predictions of cable tension, cable angle at towing ship, and body depth for the bare-cable case. The best agreement between the experimental data and the data predicted by Method 1 is obtained with a cable drag coefficient of 1.5 and a tangential force factor of 0.02. Method 1 is the one described in DTMB Report 687 "Tables for Computing the Equilibrium Configuration of a Flexible Cable in a Uniform Stream" by L. Pode. Method 2 is due to L. F. Whicker "The Oscillatory Motion of Cable-Towed Bodies" University of California, Series 82, May 1957. The two methods are essentially the same but differ in the loading functions which are used.

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Glauert, H.

"Heavy Flexible Cable for Towing a Heavy Body Below an Aeroplane" Aeronautical Research Committee, Reports and Memoranda No. 1592 (T 3498), February 1934 (London, Great Britain).

R. & M. 1312* dealt with the form assumed by a light flexible cable which is used to tow a heavy body behind an aeroplane and the stability of the towed body. In R. & M. 554** a heavy flexible cable was analysed but no numerical solutions were obtained. The present report presents curves which will be useful in many engineering applications.

* Glauert, H. "The Stability of a Body Towed by a Light Wire" R.& M. 1312, 1930.

** McLeod, A. R. "On the Action of Wind on Flexible Cables, with Applications to Cables Towed Below Aeroplanes and Balloon Cables" R. & M. 554, 1918.

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Graham, R. D., M. A. Frost and J. C. Wilhoit, Jr.

"Analysis of the Motion of Deep Water Drill Strings - Part 1: Forced Lateral Motion" Journal of Engineering for Industry, Vol. 87, Series B, May 1967.

An equation of motion for a drill string is derived. Two types of drill-string are considered: a beam having a constant axial tension and a perfectly flexible cable under variable tension. The effect of roll is considered in another study; in the present paper the drill-string is considered built-in at the ocean floor and is displaced harmonically by the ship at the other end.

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Havelock, T. H.

"The Resistance of a Submerged Cylinder in Accelerated Motion" Quarterly Journal of Mechanical and Applied Math., Vol. II, Part 4, 1949.

This paper deals with the determination of resistance to motion of a circular cylinder at a constant depth below the free surface. The motion starts from zero and has uniform acceleration. The resistance is expressed as the sum of two terms; one corresponds to the wave resistance for uniform velocity and the other may be considered as an effective inertia term.

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Horton, J. L. and R. A. Yagle

"Analysis of Assumed Mooring Arrangement for Maritime Class Ship" Marine Technology, pp. 257-266, July 1968.

This paper deals with an analysis of wind conditions which would be sufficient to establish the sequence necessary to cause parting of one line, followed by parting of second and third lines and, finally, by full failure of the mooring arrangement. Wind-tunnel tests on a model of the ship are reviewed.

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Howe, James F.

"Determination of Stresses in Wire Rope as Applied to Modern Engineering Problems" Transactions of the ASME, Vol. 40, pp. 1043-1093, 1918.

This paper deals with the derivation of formulae to compute direct and induced stresses developed in wire ropes by static or moving tension, bending, and horizontally suspended loads.

The values for the bending stresses produced in ropes that are passed over sheaves, as determined by the formula of Reuleaux, Rankine, Unwin and Hewitt are correct only for ropes composed of straight wires. Owing to the twisting of the wires in the formation of modern rope, the actual bending stress in it is much smaller than in a solid bar, and its true value, S, may be computed by replacing in the fundamental assumptions the modulus of elasticity of a solid bar, with $E_R$, the experimental value of the modulus of elasticity of the rope as a whole; thus the Reuleaux formula becomes

$$S = E_R(d/D)$$

where d is the diameter of the wire in the rope, and D the diameter of the bend.

The author develops a method for determining the moduli of elasticity of both strands and rope in cases where experimental data are not available. In regard to the customary practice followed in specifications, general remarks are offered on the required proportionality between the sheave diameters and the size of the rope, the manner of classifying strengths in the manufacturer's rope catalog, and the special requirements in the physical properties of the wire forming the rope.

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Isakovich, M. A. and L. N. Komarova

"Longitudinal-Flexural Modes in a Slender Rod", Soviet Physics, Acoustics
Vol. 13, No. 4, April-June 1968,

The present paper deals with longitudinal-flexural waves in a curved slender rod whose axis forms a plane curve. A zero-moment theory of the modes in the rod is given; some examples are worked out. The authors show that it is possible to tune the rod to different frequencies by varying the curvature. The phenomenon of the "Singing Saw" is discussed.

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Jeffrey, N. E.

"Influence of Design Features on Underwater Towed System Stability"
Journal of Hydronautics, Vol. 2, No. 4, October 1968.

Development of faired cables has increased the feasible speed and depth of underwater towed systems, but a much more refined approach is now needed to obtain good dynamic stability with passively stabilized systems.

Parametric analytical stability studies have demonstrated some fundamental effects of cable and body designs and their interactions on body behavior. These studies were based on a relatively simple mathematical model, which included approximate cable configuration parameters and body virtual masses and inertias. Results demonstrate the existence of a mode dominated by cable configuration, a mode dependent on cable-body coupling effects, a mode primarily affected by body design and three modes unlikely to be of practical importance. Relative effects of primary cable and body design features are shown in root-locus form, and conclusions are drawn concerning their significance to the over-all system. The study shows that of the six modes of motion exhibited, three are likely to be significant and three insignificant for statically stable depressed bodies of the type studied.

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Kenworthy, Ray W. and Vernon A. Jennings

"The Modes of Vibration of a Semi-Flexible Rod under Tension" Journal of the Acoustical Society of America, Vol. 24, No. 1, pp. 60-61, Jan 1951.

This paper deals with the determination of frequencies of vibration of a semi-flexible rod. The restoring force for small displacements is the result of stiffness and of tension. The governing differential equation is

$$T\frac{\partial^2 y}{\partial x^2} - QSK^2\frac{\partial^4 y}{\partial x^4} = \rho S\frac{\partial^2 y}{\partial t^2}$$

where T: tension; Q: modulus of elasticity; S. area of cross section; K: radius of gyration of the cross section and $\rho$: density of the beam material.

Good agreement is obtained between analytical and experimental results for the first ten modes in the case of a rod with both ends clamped.

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Kimura, Haruo

"A Study on the Propagation of Waves in Wire Rope as Affected by Structural Damping" Proceedings of the 14th Japan National Congress for Applied Mechanics, 1964.

The analysis on the propagation of waves in a wire rope subjected to an impulsive velocity at its end is presented. The rod is semi-infinite and it is assumed that the stress-strain relation is given by

$$\sigma(i\omega) = (1 + ig) E \varepsilon(i\omega)$$

where the expressions $\sigma(i\omega)$ and $\varepsilon(i\omega)$ indicate that they are complex sinusoidal variables of the frequency. The author states that it is more accurate to take into account structural and viscous damping.

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Lacey, H. M.

"Specialized Equations of Motion of a Towed Underwater Vehicle" Report I-77 (Interim) May 1965, U.S. Navy Mine Defense Laboratory, Panama City, Florida.

In the development of towed underwater vehicles, it would be desirable to be able to predict possible vehicle designs and control system circuitry for attaining specified flight characteristics of the vehicle. In pursuance of these objectives, a study was initiated to investigate the feasibility of using analytical techniques for describing the dynamic flight characteristics of a vehicle of this class in controlled flight in the vertical plane. The purpose of this report is to formulate the three specialized equations of motion of the vehicle (for motion in the vertical plane only) which may serve as a basis for the theoretical analysis.

Laird, Alan D. K.

"Flexibility in Cylinder Groups Oscillated in Water" Journal of the Waterways and Harbors Division; Proc. ASCE, August 1966, p. 69.

The present paper deals with a model study of forces and moments acting on several piling configurations. Several parameters are varied: orientation of the group with respect to the flow, support flexibility, etc.

Landweber, L.

"Hydrodynamic Forces on an Anchor Cable" DTMB Report R-317, Nov. 1947.

This report presents curves from which the magnitude and direction of the tensions in the anchor cable can be determined when the drag of the ship, velocity of the current, depth of the water and type and length of the anchor cable are known. Formulas are given for ship drag, current parameter, breaking strength of wire-rope and chain cables, safe working loads on cables and holding power of an anchor.

Landweber, L. and M. H. Protter

"The Shape and Tension of a Light Flexible Cable in a Uniform Current" Journal of Applied Mechanics, pp. A 121 - A 126, 1947.

This paper deals with several cases of a towing cable in which the frictional forces as well as the normal forces are taken into account in determining the configuration of the cable. The weight of the cable is neglected. Several towline situations of practical interest are considered as applications of use of equations and curves presented in the paper.

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Laura, Patricio A., Hendrikus Vanderveldt and Paul Gaffney

"Acoustic Detection of Structural Failure of Mechanical Cables" Journal of the Acoustical Society of America, (February) 1969.

Mechanical cables have long been used for towing operations, remote control of equipment, communication lines and other operations demanding a transfer of power through a flexible link. Since the cable is one of the most important components in these systems, sensors which transduce the behavior of the cable when in operation are of utmost importance. The recent loss of the deep submersible "Alvin" makes urgent the finding of suitable methods to detect deterioration of the cable prior to complete failure.

Several authors have discussed the possibility of using acoustic means for detecting crack propagation and failure in the case of continuous media. Accelerometers are attached to the specimen under study. When small flaws or cracks propagate, a stress wave is emitted from the crack, which is detected with a standard accelerometer. It seems reasonable then to use a similar detection system in the case of stranded cables. These cables consist of tightly woven strands. Each strand in turn is made up of tightly wound wires. Consequently, when an increasing tensile load is applied the individual wires fail first, and strands later. The energy that is released travels along the cable in the form of a stress wave which can be detected by an electronic transducer. The present letter presents some preliminary results obtained on stranded cables which could prove of interest to some investigators.

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Lyon, Richard

"The Transmission of Vibration by Towed Cables" Bolt, Beranek & Newman, Inc. Report No. 934, May 1962.

There are steady and time varying forces acting on a cable dragged through a fluid. These forces are applied to the cable by the attachments at its ends and fluid reactions distributed along its length. The steady forces arising from weight, fluid drag and end loads determine the equilibrium shape of the cable. The present report is mainly concerned with time varying loads and the transmission of these vibrations. Time varying loads are caused by motion of the towing vehicle, unstable flow (vortex shedding) about the cable and/or the turbulence of the cable boundary layer and the turbulent wake of the towing craft.

It is assumed that Reynolds number is in the range $10^4 \leq R \leq 10^5$; the shedding frequency $25 \leq f_s \leq 250\ H_z$ and that the damping coefficient per unit length due to drag at high Reynolds number is of the order of $r_D = \rho_f \cdot C_D \cdot V \cdot D$ where $\rho_f$: fluid density, V: velocity and D: diameter of the cable. It turns out that the loss factor is sufficiently low so that waves can propagate without inordinate attenuation in a wave-length and resonances may be excited by the unsteady forces.

The report uses the mathematical model derived by Phillips[1]:

$$\frac{\partial^2 y}{\partial x^2} - 2\eta \frac{\partial y}{\partial x} - 2\eta V_t^{-1} \frac{\partial y}{\partial t} - a^{-2} \frac{\partial^2 y}{\partial t^2} = F_c(t)\, T^{-1}$$

where $\eta = \rho_f C_D V^2 D \sin 2\alpha / 4T$ is a measure of the relative importance of drag and tension forces, $V_t = V \cdot \cos \alpha$. The motion is parallel to the flow for a string of tension T having an average angle of incidence $\alpha$ with respect to the velocity V. The case of linearly varying T is also studied.

It is concluded that vortex shedding by the cable may be expected to cause more vibration transmission to the towed body than ship, wake motion or boundary layer noise.

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[1] W. H. Phillips "Theoretical Analysis of Oscillations of a Towed Cable" NACA, T. N. 1796, January 1949.

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McLoad, K. W. and W. E. Bowers

"Torque Balanced Wire Rope and Armored Cables" Transactions of the 1964 Buoy Technology Symposium

Torque-balanced wire ropes and armored cables offer significant advantages by reducing stretch and the amount of energy stored in the cable. The paper discusses cable properties and operational problems.

A figure of merit Q is defined as

$$Q \propto E\left(\frac{S}{\rho_1}\right)^2$$

where E: modulus of Elasticity

S: ultimate strength

$\rho^1$: effective density of material in water

By this measure, titanium is the best material. Steel and dacron follow. The parameter Q is actually defined as

$$\frac{(\text{weight/strength}) \times (\text{weight/size})}{(\text{self stretch})}$$

McNiven, H. D. and D. C. Perry

"Axially Symmetric Waves in Finite, Elastic Rods" Journal of Acoustical Society of America, Vol. 34, No. 4, April 1962.

The paper develops an approximate theory of symmetric vibrations of elastic rods. Frequency equations are developed and the lower resonant frequency of axially symmetric motion of a circular, elastic, finite rod is calculated and presented in graphs.

Meier, J. H.

"Energy Transmission by Stress Waves in Prismatical Bars" Experimental Mechanics, May 1965, pp. 135-141.

This paper deals with energy transmission by stress waves in prismatical bars. Experiments were conducted on straight and curved bars. The effects of cross-section impedance mismatch and length mismatch of impacting bars in studied. The author is apparently unaware of the technical literature available on vibrations and effects of dispersion in curved bars.

Michel, Douglas, Pikul, R. P. and Kosser, A. F.

"Forces due to Travelling and Standing Waves in Cables" Interim Report No. C-70; The Kaman Aircraft Corporation, August 1954.

If an antenna-supporting vehicle is disturbed from its steady state flight by a gust, then it, in turn, will disturb the end of the cable to which it is attached. This disturbance will travel down the cable to the mooring point, reflect and travel up the cable to the vehicle and disturb it again. It is clear that the cable dynamics must be included when designing an automatic position stabilising device for the vehicle. The purpose of the present report is to devise methods for determining the transient force at the mooring point due to a disturbance of the vehicle.

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Middleton, G. W. and J. W. N. Fead

"Fundamental Cable Analysis" Developments in Mechanics, Vol. 4, Johnson Publishing Co. (proceedings of the Tenth Midwestern Mechanics Conference) pp. 631-645.

This study contains equations which are derived for simple cables giving a direct solution under the condition of uniform horizontal distribution of dead, ice, and wind loads. This analysis is different from previous cable treatments in that it specifies the maximum force in the cable rather than assuming the amount of sag in the cable. Equations are also derived for cables which carry concentrated loads in addition to the above loads. When the maximum force which is to appear in each cable of an antenna system is specified and the cables are considered as inextensible, it is proved that the system is determinate.

The equations are not linear, and an iterative process is required to obtain a solution of the equations. Such a process is described here. The results are listed for comparison, and these were obtained by computation and by measurement from a model.

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Miller, Eugine and W. C. Webster*

"An Analysis of Large Object Lift Systems" ASME Underwater Technology Division, 1967 National Conference.

The raising (or lowering) of a very large object, such as a submarine, in the open sea is an extremely difficult and costly operation. A major problem is the large seaway induced forces and motions. This paper deals with analysis and control of these forces in two types of large object lift systems. One system involves use of two surface ships lifting a submarine with cables. The other system consists of standard winches on minimum response surface floats instead of conventional surface ships.

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*See also: Technical Report 613-1; Hydronautics Incorporated, Dec. 1966.

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Milner, James LaMar

"Free Vibration of a Rotating Beam-Connected Space Station" NASA TN D-4753, September 1968.

The free vibrations of a rotating beam-connected space station are analyzed. The space station is composed of two space modules connected by a flexible beam. The system is made to spin in the plane of its orbit. The author presents a brief, but useful, survey of the literature.

Several authors* have been concerned with dynamics of cable-connected space stations.

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*See, for instance:

Targoff, W. P., "On the Lateral Vibration of Rotating, Orbiting Cables" AIAA Paper No. 66-98, Jan. 1966.

Tai, C. L. and M. Loh, "Planar Motion of a Rotating Cable-Connected Space Station in Orbit", J. Spacecraft Rockets, Nov. 1965.

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Morales, Ramon C.

"Shear-Volume Method of Solving Tensions in Cables" Journal of the Structural Division, ASCE, pp. 111-118, 1968.

A method to determine stresses and deformations in cables subjected to static loading is presented. The method eliminates the need for calculation of cable movements and is based on the imposed loading.

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Morley, L. S. D.

"Elastic Waves in a Naturally Curved Rod" Quarterly Journal of Mech. and Applied Math., Vol. 14, Pt. 2, pp. 155-172, 1961.

The problem of propagation of free elastic waves of small amplitude in a naturally curved rod is studied. It is assumed that the neutral axis forms a plane curve of constant radius. A Timoshenko type equation is obtained in the case of slight curvature and a simple relation with the phase velocity of flexural waves in the initially straight rod is found.

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Morrow, B. W. and Wen F. Chang

"Determination of the Optimum Scope of a Moored Buoy" Journal of Ocean Technology, Vol. 2, No. 1, pp. 37-42; 1967.

The method described in this paper is expected to give a good estimate of the magnitude of the scope of minimum tension, as well as the relationship between tension at the anchor, maximum tension and length of mooring line.

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Moser, J. R. and R. F. Spencer

"Predicting the Magnetic Fields from a Twisted Pair Cable" USL Report No. 848, December 1967.

A theory that predicts the magnitude of low-frequency magnetic fields near a current-carrying twisted-pair cable is developed. By asymptotically expressing the theoretical results, it is shown that the magnetic fields from a twisted-pair cable of pitch distance p decrease exponentially with the radial distance from the center of the cable. The asymptotically expressed result is verified experimentally for a radial distance as large as (3/2)p. At such a distance, the maximum fields from the cable are shown to be 50 db below that from a two-wire line (two parallel wires), even though both the cable and the wire line are carrying the same amount of current.

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Muki, R. and E. Sternberg

"On the Diffusion of an Axial Load from an Infinite Cylindrical Bar Embedded in an Elastic Medium" T.R. No. 16, California Institute of Technology, September 1968.

This report deals with the decay of resultant axial force in an infinite cylindrical elastic bar which is bonded to an infinite elastic medium of distinct mechanical properties. The bar is subjected to an axial loading confined to, and uniformly distributed over, one of its cross-sections. An approximate solution applicable to a bar of arbitrary shape is also developed.

Naval Air Development Center

"Dynamic Characteristics of Underwater Cables Flow Induced Transverse Vibrations" Report No. NADC-AE-6620, 6 September 1966.

The dynamic behavior of strumming hydrophone cables associated with air-launched sonobuoy surveillance systems is reported for a 200 to 3000 Reynolds number range. Four areas are considered, experimental techniques, cable tuning effects, frequency scaling law and analysis of the motion of the terminal mass using a discrete element system.

O'Brien, W. Terence

"Behavior of Loaded Cable Systems" Journal of the Structural Division, Proc. ASCE, October 1968, p. 2281.

Previous papers have presented a general method of analysis for a freely suspended cable subjected to a three-dimensional system of concentrated and distributed loadings. In the proposed method, three orthogonal components of cable force at one support are adopted as redundant forces, the cable-force components at each discontinuity in the loaded shape are computed from equilibrium equations, and the compatibility equations for the complete cable are used to check the assumed values of the redundants.

Corrections to the assumed forces are made from the computed geometrical results using formulas which generate a second-order rate of convergence When coupled with the speed of an electronic digital computer, the proposed method provides an accurate tool for the analysis of various types of freely suspended and interconnected cable systems. One particular application of the preceding method of analysis by the writer has been a theoretical investigation of the behavior of freely suspended cable systems subjected to point loading in any direction. The purpose herein is to quantitatively describe this fundamental behavior of loaded single-cable systems and to indicate the effect of various system parameters on cable response. Although restricted to systems subjected to single loads, the results can be used as a basis from which the behavior of more complex loading systems can be estimated.

Osinski, Z, and Wasilewski, Z,

"Damped Vibrations of Mass Hung on the Steel Rope with Nonlinear Elasticity and Damping" Zagadnienia Drgan Nieliniowych (Nonlinear Vibration Problems) (Poland), 1964.

It is assumed that when the rope is stretched the resultant force is due to an elastic plus a damping response. The mechanical characteristics of the rope are obtained experimentally

Paidoussis, M. P.

"Stability of Towed, Totally Submerged Flexible Cylinders" Journal of Fluid Mechanics, Nov 1968, Vol. 34, Part 2, pp. 273-297.

A general theory is presented to account for the small, free lateral motions of a flexible, slender, cylindrical body with tapered ends, totally submerged in liquid and towed at steady speed U. For particular shapes of the ends and length of tow-rope, it is shown that the body may be subject to oscillatory and non-oscillatory instabilities for $U > 0$; at small U, these instabilities correspond to those of a rigid body. At higher U, the system generally regains stability in the above modes, but may be subject to higher-mode, flexural oscillatory instabilities. The critical conditions of stability are calculated extensively and the effect on stability of a number of dimensionless parameters is discussed. It is shown that optimum stability is achieved with a streamlined nose, a blunt tail and a short tow-rope.

Some experiments are described which were designed to test the theory. Rubber cylinders of neutral buoyancy were held in vertical water flow by a nylon "tow-rope". Provided the tail was streamlined and the tow-rope not too short, 'criss-crossing', non-flexural oscillations developed at very low flow. Increasing the flow, these oscillations ceased and the cylinder buckled like a column; subsequently higher-mode flexural oscillations developed. However, for a sufficiently blunt tail and short tow-rope, the system was completely stable.

The experimental observations are generally in qualitative agreement with theory. Quantitative comparison of the various instability thresholds and stable zones between experiment and theory, based on estimated values of some of the theoretical dimensionless parameters, is also fairly good.

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Parkinson, G. V. and T. V. Santosham

"Cylinders of Rectangular Section as Aerolastic Nonlinear Oscillators"
Contributed by the Machine Design Division for presentation at the

Vibrations Conference, Boston, Mass., March 29-31, 1967, of the American Society of Mechanical Engineers.

A quasi-steady two-dimensional theory of galloping oscillation of bluff cylinders is applied to a cylinder of rectangular section with section aspect ratio 2 in uniform air flow. Force measurements on the stationary cylinder, needed for the theory, were made using a wind-tunnel balance, and observations of galloping in the wind tunnel were made on two sizes of rigid cylinder mounted on springs, using several levels of damping over a range of wind speeds. Wake vortex frequency measurements by hot-wire anemometer helped to define the wind speed range of validity of the galloping theory, and within this range, good agreement is found between theory and experiment. An extension of the theory to include effects of the wake vortices leads to a prediction of asynchronous quenching of galloping oscillation of a cylinder of square section in water flow.

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Phillips, William H.

"Theoretical Analysis of Oscillations of a Towed Cable" NACA, Technical Note No. 1796, 1949.

It has been observed that above certain airspeeds towing cables experience a violent motion which involve strong oscillations of the cable. The present report shows that oscillations travelling down wind along the cable are amplified by aerodynamic forces when the air speed is greater than the speed of propagation of waves along the cable and they are slightly damped when smaller. Waves traveling upwind are always damped. This theory provides a possible explanation for the violent motions of towed airspeed heads which appear above a certain speed. These oscillations are attributed to cable oscillations which originate near the airplane and are increased by aerodynamic forces as they travel down the cable. It is pointed out by the author that the body has frequently broken loose from the cable even though the attachment was designed to withstand a load twenty five times the weight of the body.

It is shown that the governing differential equation of motion is

$$\frac{\partial^2 y}{\partial x^2} - 2\eta \frac{\partial y}{\partial x} - \frac{2\eta\gamma}{V_0} \frac{\partial y}{\partial t} = \frac{1}{a^2} \frac{\partial^2 y}{\partial \tau^2}$$

The results could be extended to the case where the bending rigidity of the cable must be considered also.

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Plum, John

"Proposed Methods of Reducing the Cable Load and Tension of High-Speed Towing Targets" DTMB Report 666, Sept. 1948.

This report analyzes the inter-relationship between the drag of a target and certain properties of the towing cable, namely: diameter, length, weight, drag, tension and load. A method of towing is discussed by which cable tension and cable load on a target can reduced. Towing speed can be increased considerably. The report presents also an analysis of the changes in cable tensions and cable loads which take place during a 180 degree turn.

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Pode, Leonard

"An Analysis of Cable and Housing Requirements for a Deep-Towed Body at High Speed" DTMB, Report 661, November 1948.

This report deals with the analysis of a body with a negative lift-drag ratio in order to overcome the positive lift of the cable. Operationally it is necessary in some occasions to tow a body through water at a high speed keeping it at a fixed position in relation to the towing vessel.

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Pode, Leonard

"An Experimental Investigation of the Hydrodynamic Forces on Stranded Cables" DTMB Report 713, May 1950.

The validity of the sine-square law is discussed. According to this law the coefficient

$$C_N = \frac{N}{\frac{1}{2}\rho V^2 d}$$

(where N is the normal component of the hydrodynamic force acting on stranded cables per unit length, $\rho$ is the density of the water, U: speed of the stream and d the diameter of the cable) may be written $C_n = C_r \cdot \sin^2\phi$ where $C_r$ does not vary with $\phi$ ($\phi$ :angle between the cable and the stream). It is concluded that the sine-squared law holds fairly well for small inclinations of the cable to the stream. At small angles the coefficient of the side force $C_s$ seems to vary linearly with the angle.

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Pode, Leonard

"Tables for Computing the Equilibrium Configuration of a Flexible Cable in a Uniform Stream" DTMB Report 687, March 1951.

The purpose of these tables is to facilitate the determination of the shape and tensile stresses of a flexible cable moving in a fluid when neither the frictional drag nor the weight of the cable can be neglected. It is assumed that the entire cable lies in a plane.

Pode Leonard and Louis Rosenthal

"Cable Function Tables for Small Critical Angles" DTMB, Supplement to Report 687, September 1955.

These supplementary tables cover the range of critical angles from 0 to 10 degrees. The critical angle $\phi_c$ is related to the weight parameter, w = W/R by the equation

$$\phi_c = \cos^{-1}\left(-\frac{w}{2} \pm \sqrt{1 + \frac{w^2}{4}}\right)$$

where W: weight of the cable, in water, per unit length

R: drag per unit length when the cable is normal to the stream.

Plunkett, R.

"Static Bending Stresses in Catenaries and Drill Strings" J. of Eng. for Industry, Vol. 89, Series B, February 1967.

The differential equation of bending of a stiff string is derived:

$$EI \frac{d^2\theta}{dZ^2} + h \cos \theta - Z \sin \theta = 0$$

where $\theta$: slope angle

Axial elongation is derived. The paper shows that small stiffness causes an effect only in boundary regions near the end supports; the deviation from the catenary can be found as a rapidly converging series.

If one assumes that the string is in a flow current, the problem will be interesting from the "cable" viewpoint.

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Poffenberger, J. C. and R. A. Schulz

"Conductor Damping and Vibration Problems" Paper presented at the Transmission and Distribution Section, Canadian Electrical Association, March 23, 1966.

Aluminum has superseded copper and is the principal metal used in overhead power conductors. EC-H19 is the most popular aluminum base conductor. It has outstanding features but it also has some performance limitations from a mechanical standpoint: it is susceptible to vibration and fatigue. Serious consideration must be given to conductor damping. The paper contains 80 references.

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Pugsley, A. G.

"On the Natural Frequencies of Suspension Chains" Quart. Journal Mech. and Applied Math., Vol. II, Pt. 4, 1949.

A simple theory of the oscillations of a uniform suspension chain is presented. Semi-empirical expressions for the first three natural frequencies are derived and compared with experimental results:

$$n_1 = \frac{1}{2\sqrt{2}} \left(\frac{g}{d}\right)^{1/2} \left(1 - \frac{3d^2}{S^2}\right)$$

$$n_2 = \frac{1}{2\sqrt{2}} \left(\frac{g}{d}\right)^{1/2} \left(1 - \frac{1.5d^2}{S^2}\right)$$

$$n_3 = \frac{1}{2\sqrt{2}} \left(\frac{g}{d}\right)^{1/2} \left(1 - \frac{0.7d^2}{S^2}\right)$$

where

s: chain length

d: central dip

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Putnam, Abbot A.

"Flow-Induced Noise and Vibration in Heat Exchangers" ASME Paper 64-WA/HT-21; presented at the Winter Annual Meeting, New York, N.Y., Nov. 29 - Dec 4, 1964.

This is a survey-type paper on flow-induced noise, vibration and related problems in heat exchangers. The types of vibrations are discussed; vortex shedding, acoustic oscillation and tube vibration (self induced and coupled). The paper concludes that little basic advance in the understanding of flow-induced vibrations and noise in heat exchangers has taken place since Putnam's paper[1]. The paper contains and extensive bibliography on fluid-excited tube vibrations.

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[1] Putnam, A.A. "Flow Induced Noise in Heat Exchangers" Trans. ASME, Series A, p. 417, 1959.

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Rakoff, Frank B.

"Effects of Certain Ship Motions on Cable Tensions in Systems for Handling Submerged Bodies" Underwater Sound Lab., Report No. 558, August 1962.

Conditions for zero towline tension of any fishship combination are studied. The report shows that the towline tension is zero when the downward magnitude of the acceleration of the towpoint of the ship is greater than the downward acceleration of the fish. This phenomenon can occur because the only forces available to accelerate the fish are its water weight and its vertical drag. The report gives equations describing the path of the towed body and the consequences of the ultimate recapture of the body.

Reber, R. K.

"The Geometric Configuration and the Towing Tension of the System of Cables of a Mark IV Sweep" Report No. 53; Minesweepers and Mines Sweeping Section, Bureau of Ships, May 1942.

It is the purpose of this report to consider further the theory of single towed cables and to extend the theory to the system of cables of a Mark IV sweep. The dependence of the size and shape of the loop and of the tension on the station-keeping distance is considered.

Reber, R. K.

"The Configuration and Towing Tension of Towed Sweep Cables Supported by Floats" Report No. 75, Navy Dept., Bureau of Ships, Minesweeping Section, February 1944.

Expressions for the configuration and towing tension of towed sweep cables are developed taking into account forces due to the drag of the floats on float-supported cables.

Reddy, M. N.

"Lateral Vibrations of Plane Curved Bars" Journal of the Structural Division, Proc. of the ASCE, October 1968.

The flexibility approach presented herein provides a systematic procedure for the frequency analysis of lateral vibrations of plane bars. It is observed from the numerical examples that the accuracy is very good even with a few segments. The bar approximated by n degrees of freedom appears to yeild at least n/2 lowest frequencies within 2% error. A general program for IBM 7040 is written and can solve for the natural frequencies of lateral vibrations of any plane bar with not more than two segments meeting at any division point. Numerical examples are shown to demonstrate the theory and the results compared with the available solutions.

Relf, E. F. and E. Ower

"The Singing of Circular and Streamline Wire" Reports and Memoranda No. 825, (Ae. 76) March 1921, Great Britain.

The present study deals with an investigation of the singing note heard when a circular wire or a yawed streamline wire is moved through the air at considerable speed. It is established that the singing note has the same frequency as that of the periodic eddies produced behind the wire.

Reyle, S. P. and J. W. Schram

"Steady-State Three-Dimensional Analysis of Towed System" Contributed by the Petroleum Division of the American Society of Mechanical Engineers for presentation at the division's Joint Conference with the Pressure Vessels and Piping Division in Dallas, Tex., September 22-25, 1968.

This investigation is a study of the three-dimensional motion of a cable-body towing system. By assuming that the towline is continuous, completely flexible, and inextensible, three first-order differential equations of motion are developed in terms of velocity components normal and tangential to the towline. To solve these equations, normal and tangential towline forces are developed. By a Runge-Kutta technique, the steady-state expressions are numerically integrated. Predictions of body depth, towline tension, and kiting angle at the surface compare favorably with experimental data. Also, distance of the body behind the ship is virtually unaffected by movement of the body out of the towing plane.

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Richardson, William S.

"Buoy Mooring Cables, Past, Present and Future" Transactions, 2nd International Buoy Technology Symposium, 1967, Washington, D. C.

The author states that the most serious problem in buoy technology is the design of mooring cables. No single technical development is as important to the future of oceanography as the ability to moor buoys in the open ocean for extended periods of time. The different modes of failure of cables are analyzed.

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Ringleb, F. O.

"Motion and Stress of an Elastic Cable Due to Impact" Journal of Applied Mechanics, pp. 417-425, Sept. 1957.

This paper deals with the determination of displacements and stresses of an initially straight elastic cable one point of which suddenly moves with a constant vector velocity.

In 1948 the author derived, among other impact relations, for the stress in an elastic cable due to perpendicular impact with the velocity $V_o$ the approximate formula:

$$\frac{\sigma}{E} \approx \frac{T}{E} = \left(\frac{1}{2}\right)^{2/3}\left(\frac{v_o}{c}\right)^{4/3} \qquad (1)$$

where C = $(E/\rho)^{1/2}$ (longitudinal wave velocity).

This formula has been used subsequently for the computation of the impact stress in the deck pendant of an aircraft arresting gear.

The present paper discusses more general results, including the determination of stresses when the cable is subjected to oblique impact, The main result derived in this paper is the formula:

$$\left(\frac{v_0}{C_0}\right)^2 + 2\frac{v_0}{C_0}\left[\left(\frac{\sigma}{E}\right)^{1/2}\left(1+\frac{\sigma}{E}\right)^{1/2} - \frac{\sigma-\sigma_0}{E}\right]\cos\beta$$

$$= 2\frac{\sigma-\sigma_0}{E}\left(\frac{\sigma}{E}\right)^{1/2}\left(1+\frac{\sigma}{E}\right)^{1/2} - \left(\frac{\sigma-\sigma_0}{E}\right)^2 \qquad (2)$$

which determines the oblique impact stress $\sigma$ for a given impact velocity $v_0$ and a given impact angle $\beta$. $\sigma_0$ is the initial stress of the cable; E its elasticity modulus and $C_0 = (E/\rho_0)^{1/2}$ ($\rho_0$ is the mass density of the cable at zero stress).

A graph is given for the evaluation of Eq. (2). The theoretical results are compared with tests on aircraft arresting gears carried out at the Naval Air Engineering Facility (Ship Installations) Philadelphia, Pa.

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Ritter, Owen

"Determination of Reliable Wire Rope System for Application to the Deep Submergence Systems Program (DSSP)/Large Object Salvage System (LOSS)" Progress Report No. 1, Code 027, Naval Ship Research and Development Center, October 1967.

Cable fatigue is an important problem in the DSSP and LOSS programs. In LOSS the constant tensioning system pays the lifting cable in and out over the ram tensioner and bow sheave causing cable fatigue. An investigation has been initiated to determine an acceptable wire rope lift system. A lack of definite knowledge exists for predicting bending fatigue life of wire ropes.

Research efforts at other institutions is discussed and recommendations for future research are stated.

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Saito Atsushi and Norio Hirai

"Photoelastic Study of Chain Link" (2nd Report) Proceedings, 14th Japan National Congress for Applied Mechanics, 1964.

Three dimensional photoelasticity is used to determine the stress field in chain links. Experiments are run for several specimens. Curves with stress concentration factors are given. These curves are useful in design work.

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Saxon, David S. and A. S. Cahn

"Modes of Vibration of a Suspended Chain" Quart. Journal Mech. and Applied Math., Vol. VI, Pt. 3 (1953).

A method for calculating the natural frequencies of a suspended inextensible chain vibrating with small amplitude in the plane of the catenary forming the equilibrium configuration. An asymptotic solution of the linearized equation of motion is obtained.

The equations of motion are:

$$\frac{\partial^2 x}{\partial t^2} = \frac{\partial}{\partial s}\left(T\frac{\partial x}{\partial s}\right)$$

$$\frac{\partial^2 y}{\partial t^2} = \frac{\partial}{\partial s}\left(T\frac{\partial y}{\partial s}\right) - g$$

where T(S,t) is the tension at any point of the string. In addition

$$\left(\frac{\partial x}{\partial S}\right)^2 + \left(\frac{\partial y}{\partial S}\right)^2 = 1$$

Schneider, L., T. Mahan and L. Grady Burton

"Tow Cable Snap Loads" ASME Paper 64-WA/UNT-8 presented at the Winter Annual Meeting, New York, N. Y., Nov.29 - Dec. 4, 1964.

When towing submerged bodies such an oceanographic instrument package, the towcable may be subjected to severe loadings because of large-amplitude ship motions. These motions first cause the cable to become slack and subsequently subject it to impact stresses when the tension is recovered. A single-degree-of-freedom system is used to represent the system.

The effect of body density and cable compliance in attenuating the dynamic stresses is discussed.

Schneider, L. and F. Nickels, Jr.

"Cable Equilibrium Trajectory in a Three-Dimensional Flow Field", ASME paper presented at the Winter Annual Meeting and Energy Systems Exposition, New York, N.Y.; Nov. 27 - Dec. 1, 1966 of the American Society of Mechanical Engineers.

Equilibrium equations are derived by considering an element of cable; the axes of coordinates are parallel and normal to the direction vector of the cable element. By starting from known or assumed boundary values of tension and cable angles at a surface buoy or towed vehicle, the complete cable trajectory may be calculated by incremental integration The integration is completed when a prescribed cable length or depth of penetration is achieved.

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Schram, J. W. and S. P. Reyle

"A Three-Dimensional Dynamic Analysis of a Towed System" Journal of Hydronautics, Vol. 2, No. 4, October 1968.

The purpose of this investigation is to study the three-dimensional motion of a cable-body towing system. By assuming that the towline is continuous, completely flexible, and inextensible, three first-order partial differential equations of motion are developed in terms of velocity components normal and tangential to the towline. In addition to these, three kinematical first-order partial differential equations are generated to describe the position of the towline in space. The boundary conditions for the system are the motion of the towing ship and the forces exerted by the towed body. The dynamic motion of the towed system is obtained by applying the method of characteristics to the equations of motion. The characteristic equations are then numerically integrated on a computer. A transfer function, which is defined as the ratio of the resultant body amplitude of motion to the amplitude of the ship motion, is developed for various towing speeds and towline lengths. The transfer function decreases as the towline length and the towing speed increase for the examples given in this paper. Also, it is shown that, if the towline is not straight, then longitudinal disturbances produce transverse disturbances and vice versa.

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Smart, J. S.

"The Temperature of Electrically Heated Cables Towed Through Water" Report No. 90, Minesweeping Section, Bureau of Ships, February 1946.

Formulas are derived for determining the temperatures developed in electrically heated circular cables towed through water. Applications to magnetic minesweeping problems are considered.

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Snoke, Lloyd R.

"Resistance of Organic Materials and Cable Structures to Marine Biological Attack" The Bell System Technical Journal, Vol. XXXVI, Sept. 1957, No. 5, pp. 1095-1127.

The present report describes the program which includes accelerated, laboratory-microbiological tests, as well as the acquisition of data from actual marine exposures of cable structures. There are two main objectives in this program: acquisition of fundamental information and accumulation of useful engineering information on materials.

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Snowdon, J. C.

"Transverse Vibration of Beams with Internal Damping, Rotatory Inertia and Shear" Journal of the Acoustical Society of America, Vol. 35, No. 12, December 1963.

This paper deals with vibrations of beams for which the presence of shear deformation and rotatory inertia cannot be neglected. It is assumed that the beam has solid-type damping (complex shear and Young's Moduli).

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Solin, John R.

"Derivation of Equations for Maximum VDS Towline Tensions Under Dynamic Conditions" Underwater Sound Lab., Tech. Memorandum No. 933-257-64 August 1964.

This report is closely related to USL Report No. 558; derives two equations for computing VDS towline tensions under dynamic conditions. A first analysis assumes negligible gravitational and damping forces; the second neglects effects of ship mass.

Stowell, E. Z. and A. F. Deming

"Vortex Noise from Rotating Cylindrical Rods" Journal of the Acoustical Society of America, Vol. 7, No. 1; pp. 190-198, Jan 1936.

Several round rods were rotated individually about the midpoint of each rod. Vortices are shed from the rods when in motion, giving rise to the emission of sound. The frequency of emission of vortices from any point on the rod is in agreement with VonKarman's formula. The paper contains several references on Aeolian tones.

Sun, T. C., J. D. Achenbach and G. Herrmann

"Effective Stiffness Theory for Laminated Media" Technical Report No. 67-4 (Northwestern University) July 1967.

A method is proposed to derive displacement equations of motion for a laminated medium. The method is applied to study the propagation of free harmonic waves in an unbounded medium.

Swope, R. D. and W. F. Ames

"Vibrations of a Moving Threadline" Journal of the Franklin Institute, Vol. 275, Jan 1963, pp. 36-55.

A linear mathematical model for the oscillations of the moving threadline between the fixed eyelet and the transverse device is derived and solved. The governing equation (the "threadline equation") is a hyperbolic second order partial differential equation which in dimensionless form is

$$\frac{\partial^2 y}{\partial t^2} + \alpha \frac{\partial^2 y}{\partial x \, \partial t} + \beta \frac{\partial^2 y}{\partial x^2} = 0$$

It should be emphasized the fact that the characterization and analysis of the oscillations of a string or yarn as it is traversed and wound on a bobbin is a problem of major interest in the textile industry.

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Takizawa, Ei-Iti and Yosikuyi Sugiyama

"On the Equation of Longitudinal Vibration of a Circular Cylinder with Moderate Thickness with Moderate Thickness under Thermal Stress" Memoirs of the Faculty of Engineering, Nagoya, Japan, Vol. 13, No. 1.

This paper deals with vibrations of a rod taking into account higher order deformations of the cross-sectional plane under thermal stress.

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Thom, A.

"Eddies Behind a Circular Cylinder" Reports and Memoranda No. 1373 (Ae. 500) December 1930, Great Britain.

This report deals with an experimental investigation of an oscillating cylinder suspended transversely in a moving fluid. The oscillations are continuous if the natural frequency of the cylinder is the same as that of the eddies which are known to be given off by a cylinder at nearly all values of Reynolds Number.

Toebes, Gerrit

"Flow Induced Structural Vibrations" Journal of the Engineering Mechanics Division, Proceedings of the ASCE, December 1965; pp. 39-66.

This paper is a survey article of "Fluidelastic" problems. A basic principle is the fact that structural deformation and fluid dynamic loading are independent. The paper is the result of a research program sponsored by NSF on fluid dynamic operators and wake mechanics for cylindrical structures.

Ueno, Keizo

"On the Tension of Towing Hawsers of Ships and also of Chain Cables of Mooring Buoys" Memoirs of the Faculty of Engineering, Kyushu University, Vol. 22, No. 2, pp. 95-117, March 1963.

The first part of the paper is concerned with the calculation of tension occuring in the towing hawser of ships when they meet regular waves and gusts assuming that the profile of a towing hawser is a catenary curve and that the weight of the hawser per unit length is constant. Water resistance is also neglected.

The second part deals with the determination of tension in chain cables of mooring buoys when ships moored in sea of some depth of water meet regular waves and gusts.

Ulrich, J. L., G. D. Mott, and D. R. Keyser

"How to Minimize Barge Damage" Ocean Industry, Vol. 3, No. 7, July 1968.

Some of the difficulties encountered in salvage problems are discussed. A common problem is that of "Slicing" or deforming the hull of the wreck with the lifting wires. This effect is also called "Cheesing". A quantitative evaluation of the problem is derived; some recommendations are made.

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Walton, T. S. and Harry Polachek

"Calculation of Non-linear Transient Motion of Cables" DTMB Report 1279, July 1959.

The problem treated is a generalization of the classical vibrating string problem in the following respects: a) the motion is two dimensional, b) large displacements are permitted, c) forces due to weight of the cable, buoyancy, added fluid mass and damping or drag are included and d) the cable is assumed to be non-uniform. Finite differences approach is used. The distributed mass of the cable is replaced by a number of masses $m_j$ attached to a weightless, inextensible line. A system of ordinary differential equations is obtained.

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Wilson, Basil and H. Norman Abramson

"A Further Analysis of the Longitudinal Response of Moored Vessels to Sea Oscillations" Texas A. & M. Research Foundation Project 24, April 1955.

This report deals with the solution of the non-linear differential equation governing the longitudinal motion of moored vessels in harbors.

Response curves for forced motions are shown. The differential equation is:

$$\frac{d^2u}{dt^2} + \left(\frac{K}{2M}\right)\frac{du}{dt} + \left(\frac{C}{2M}\right)u^n = \left(\frac{KV}{2M}\right)\cos pt - \frac{V\cdot p}{2}\sin pt$$

where u: longitudinal displacement

M: mass of the moored vessel

K: damping factor dependent essentially upon the size and shape of the vessel.

C: constant dependent upon the number and size of ropes.

V: velocity of the water relative to the vessel.

p: angular frequency of the seiche.

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Wilson, Basil W.

"Characteristics of Anchor Cables in Uniform Ocean Currents" The A&M College of Texas, Department of Oceanography and Meteorology; A&M Project 204, Technical Report No. 204-1, April 1960.

This report deals with an exact solution of the equilibrium of a flexible mooring cable subjected to a steady fluid flow whose velocity is constant with depth. The cable has uniform line density and is suspended in the vertical plane containing the terminal points. The author points out that this problem has engaged the attention of many investigators from the time of the first trans-Atlantic telegraph cable-laying. More recent and pertinent work are those papers by Landweber (1947); Dove (1950), Pode (1951); Kullenberg (1951) and Zajac (1957). Landweber, Dove and Zajac have used different mathematical approaches taking into account fluid drag normal to the axis of the cable but neglecting longitudinal drag. Pode includes tangential drag, assuming it constant along the length of the cable. This is true only if the cable approximates a straight line.

Kullenberg did not use the simplifying assumptions stated above in his analysis of a trawling cable.

Wilson's report uses the techniques developed by Kullenberg and Dove to secure solutions of the mooring cable problem within the accuracy of the conventional methods used to determine the hydrodynamic forces, in a form which can be extended to the case of steady currents which are variable in depth.

The mathematical solution obtained by Wilson follows the next procedure: a) the hydrodynamic forces acting on the cable are resolvable into components $D_n$ and $D_t$ per unit length, respectively normal and tangential to the cable. It is shown that both components are dependent on the corresponding normal and tangential components of the stream velocity, b) the two fundamental differential equations of equilibrium are unified by the use of the radius of curvature R as dependent variable and the angle of inclination $\psi$ as the independent variable.

The basic properties of the system are incorporated into two quantities, $\mu$ and $\gamma$. The former is controlled by weight and diameter of the cable, fluid velocity and density and normal drag coefficient; the latter is the ratio of tangential to normal drag coefficients. c) the resultant single differential equation for R as a function of $\psi$ is integrable mathematically. Results are presented in dimensionless form in figures and tables and define the scope (cable length/depth), stance (horizontal projection/depth), relative tensions (surface or bottom tension/depth x cable weight in water per unit length) in term of the angles of inclination with the horizontal of the cable at the upper and lower tie-points.

d) an example is given of the application of results to the mooring of ships in a tideway, e) care has been taken to check that the general solution of the problem for any value of $\mu$ and $\gamma$ yields the known solutions obtained by other investigators for particular values of $\mu$ and $\gamma$. Thus for $\mu=\infty$ & $\gamma=0$, the general solution checks with the well known catenary equations. For $\mu$ finite but $\gamma = 0$, the solution agrees with the equations of Landweber, Dove and Zajac. Also for $\mu$ finite and $\gamma \simeq 0{,}025$, agreement is obtained with the results of Pode, provided suitable allowance is made for the nature of his assumption regarding tangential drag.

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Wilson, B. W.

"Elastic Characteristics of Moorings" Journal of the Waterways and Harbors Division, Proceedings of the ASCE, 93, WW4, pp. 27-56, Nov. 1967, AMR 4778 (1968).

The author presents a collection of numerical data concerning weight, ultimate strength, fatigue strength and elastic properties of mooring ropes (nylon, dacron, manila, etc.). The behavior of mooring ropes under repeated loading is discussed. Formulas are given for calculating the dynamic effect exerted by waves on the moored ship and anchor cable.

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Woodland, Barry

"Structures for Deep Submergence" Space Aeronautics, March 1967.

Materials for operations at tens of thousands of feet below the surface of the ocean must meet special requirements: low weight, high strength, long fatigue life, etc. Problems and areas of research are outlined.

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Zabusky, Norman J.

"Exact Solution for the Vibrations of a Nonlinear Continuous Model String" Journal of Mathematical Physics, Vol. 3, No. 5, September - October 1962.

An exact solution is given for the partial differential equation

$$y_{tt} = [1 + \varepsilon y_x]^{\alpha} y_{xx}$$

which describes the standing vibrations of a finite, continuous, and nonlinear string. The nonlinearity studies, $[1 + \varepsilon y_x]^{\alpha}$ was motivated by the work of Fermi, Pasta, and Ulam (1955), where they reported on numerical studies of the "equipartition of energy" in nonlinear systems. To obtain the solution, the above equation is transformed into a linear equation by inverting the roles of the dependent ($u = y_x$ and $v = y_t$) and independent ($x$ and $t$) variables. Riemann's method of integration is applied to the problem and the solutions for t and x are written as integrals. The nature of the "inverse Riemann plane," how it is related to the initial conditions, and how one unfolds it, are discussed in detail. A general procedure is described for reinverting the solution, so that y can be written as a function of x and t. It is illustrated to order $\varepsilon$ for the above problem. It is demonstrated that $y_{xx}$ becomes singular, that is, $y_x$ develops a discontinuity after an elapsed time of order $(1/\varepsilon)$. The methods described are applicable to any nonlinear string where the coefficient of $y_{xx}$ is a function of $y_x$ only. The effect of higher spatial derivatives on the formation of the singularity is discussed.

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Zajac, E. E.

"Dynamics and Kinematics of the Laying and Recovery of Submarine Cable"
The Bell System Technical Journal, Vol. XXXVI, Sept. 1957, No. 5,
pp. 1129-1207.

The formulation of a comprehensive theory with which the forces and motions of a submarine cable can be determined is attempted. The following cases are considered: a) a cable being laid or recovered with a ship sailing on a perfectly calm sea over a horizontal bottom, b) effects of ship motion, c) varying bottom depth, d) ocean cross currents and e) the problem of cable laying control. Formulas and graphs are given. A two-dimensional stationary model is discussed first. Finally, the three dimensional stationary model is considered. The case of a cable in water-air environment is also discussed.

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## Part III

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A preliminary list of publications related to various aspects of cable systems is presented. Brief abstracts are given for those investigations which are applicable to cable and towed body systems.

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