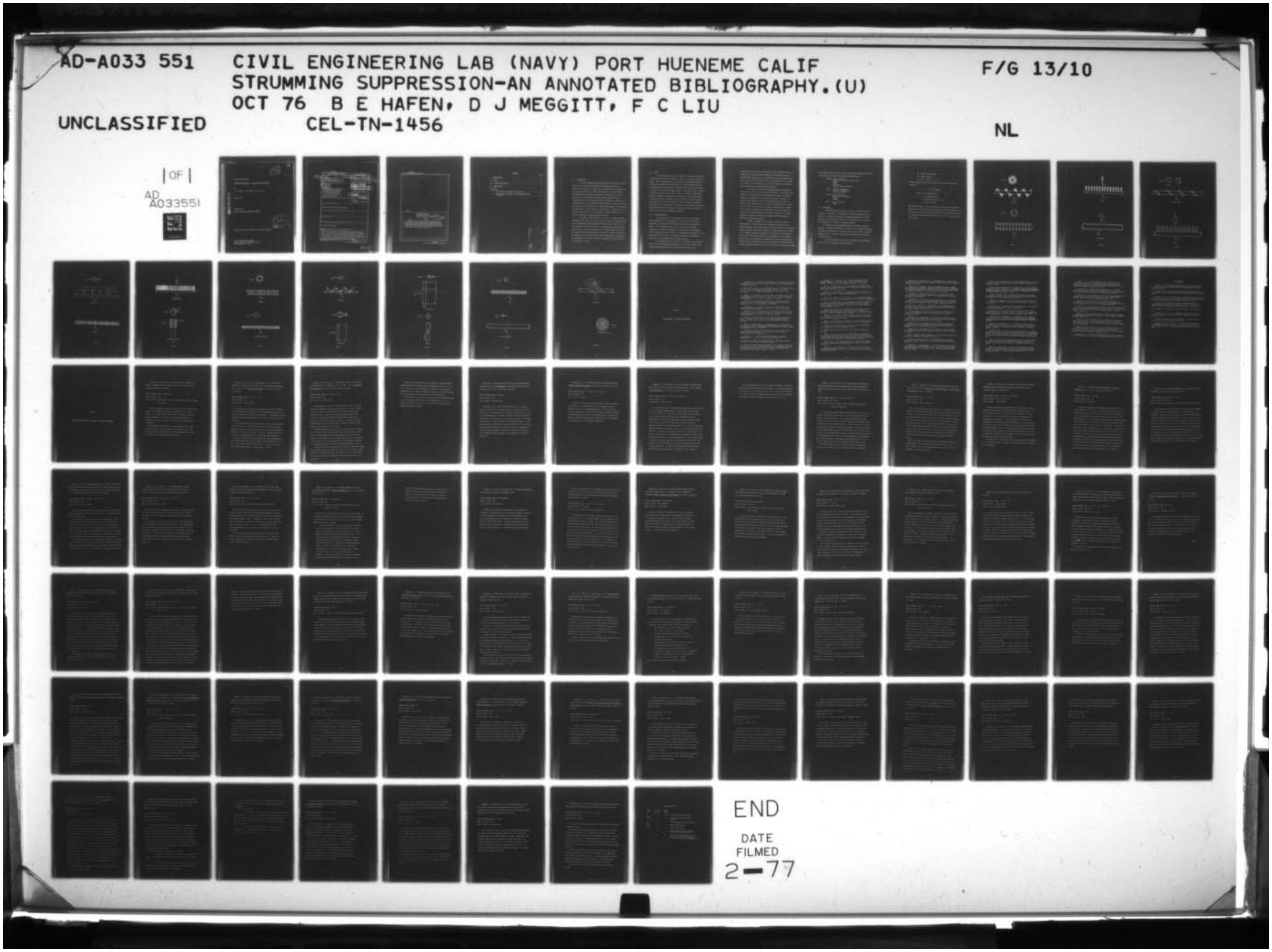

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STRUMMING SUPPRESSION - AN ANNOTATED BIBLIOGRAPHY

By

B. E. Hafen, D. J. Meggitt, and F. C. Liu

October 1976

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REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. ~~REPORT NUMBER~~ (14) CEL- TN-1456	2. GOVT ACCESSION NO. DN587013	3. ~~RECIPIENT'S CATALOG NUMBER~~ (9) Technical note Oct 75-Feb 76,
4. ~~TITLE (and Subtitle)~~ (6) STRUMMING SUPPRESSION – AN ANNOTATED BIBLIOGRAPHY.		5. ~~TYPE OF REPORT & PERIOD COVERED~~ Not final; Oct 1975 - Feb 1976
		6. PERFORMING ORG. REPORT NUMBER
7. ~~AUTHOR(s)~~ (10) B. E. Hafen, D. J. Meggitt F. C. Liu		8. CONTRACT OR GRANT NUMBER(s) (16) F52556 (17) YF52556999
9. PERFORMING ORGANIZATION NAME AND ADDRESS CIVIL ENGINEERING LABORATORY Naval Construction Battalion Center Port Hueneme, California 93043		10. ~~PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS~~ 62759N; YF52.556.999.01.201
11. CONTROLLING OFFICE NAME AND ADDRESS Naval Facilities Engineering Command Alexandria, Virginia 22332		12. ~~REPORT DATE~~ (11) Oct[redacted]976
		13. NUMBER OF PAGES 86 (12) 89p.
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. ~~(of this report)~~ Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

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

18. SUPPLEMENTARY NOTES

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

Cables; mooring; strumming.

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

Vortex-excited vibration of cables and cable systems is a commonly observed phenomenon in the ocean. This cable strumming effects the response of instrumentation, such as hydrophones, and enhances the possibility of a fatigue failure. This document presents the results of a literature search on this subject. Although the present requirement is for the reduction of cable strumming, the literature cited includes information from any attempt to suppress vibration due to flow around a biuff body.

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TN-1456 86 pp illus October 1976 Unclassified

1. Cables 2. Strumming I. YF52.556.999.01.201

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CONTENTS

I. INTRODUCTION

The Civil Engineering Laboratory, under the sponsorship of the Naval Facilities Engineering Command, is engaged in a program of research on the dynamics of cables and cable structures in the deep ocean. The program considers two specific problem areas: (1) the relatively small amplitude, relatively high frequency vibrations of cables due to periodic lift forces induced by vortex shedding (generally termed "strumming"); and (2) the large displacement, relatively low frequency or transient response to disturbances during implantment or while in place on the ocean floor, from shock waves or unsteady hydrodynamic forces associated with geostrophic, tidal, inertial or density flows. In both parts of the program, the objective is the development of effective methods for the analysis and design of subsurface cable structures.

The vortex-excited vibration of cables is a commonly observed phenomenon in the ocean. This motion frequently results in degraded acoustic or environmental sensor performance and accelerated fatigue of structural elements. Further, the drag of a strumming cable is significantly higher than that of a non-vibrating cable, producing higher stresses in the elements and greater distortion of an array in a given current field. An integral part of the research into cable strumming in this program is the development of efficient, effective techniques to suppress the flow-excited motions of cables.

II. SCOPE

The vortex-induced motions of cables and cable systems can have a detrimental effect on the system which employs the cable as a structural member. Cable strumming affects the response of instrumentation such as hydrophones and enhances the possibility of a fatigue failure; therefore, the suppression of this vibration is desirable from a structural viewpoint as well as from a system performance aspect. This report presents a survey of existing literature on this subject and is an attempt to consolidate existing information concerning the suppression of vortex-induced motion. Although the present requirement is for the reduction of cable strumming, the literature cited includes information from any attempt to suppress the vibration due to flow around a bluff body. A future report will discuss that research specifically oriented to cables as it impacts the present state of the art of cable strumming suppression.

III. SUPPRESSION DEVICES

The suppression of vortex-induced motion can be accomplished either mechanically or fluid dynamically. The system can be detuned mechanically by increasing the structural stiffness or using mechanical dampers. This detuning generally tries to ensure that the natural frequency of the system is separated by at least an order of magnitude from the frequency of vortex shedding. The installation of dampers or the stiffening of the structure is not always technically or economically feasible and a fluid dynamic solution would be needed.

Fluid dynamically, the vibrations of a cylinder can be substantially reduced by introducing disturbances on or near the surface of the cylinder which interact with the vortex-shedding mechanism. This interaction can affect the vortex mechanism in four different ways: (1) minimizing the adverse pressure gradient by influencing the point of boundary layer separation; (2) interfering with the vortex interaction in the near wake directly behind the body; (3) disrupting the vortex formation length in the wake of the body, and (4) disrupting the coherence of vortex shedding along the length of the cylinder.

The papers cited in this bibliography discuss predominantly fluid dynamic solutions to the problem of vibration. In particular, with reference to the four basic methods mentioned previously, streamlined fairings, vortex generators and studs have been used to influence the boundary layer separation points; splitter plates have been used to prevent vortex interaction; "hair" fairing, "fringe" fairing and ribbons have been used to disrupt the vortex formation length; helical strakes, "hair", ribbons, herringbone and twisted pairs of cable have been used to disrupt the spanwise coherence of the vortex shedding. No attempt is made in this paper to compare the advantages and disadvantages of these various suppression methods.

Figures 1 through 10 are included to provide a pictorial representation of the various types of suppression devices which have been investigated. Many devices such as the studs in Figure 1, the splitter plates in Figure 4, the shroud in Figure 5, the rigid guide vane in Figure 7, the "Flexnose" fairing and radial fins in Figure 8, and the rings and NACA sectional fairing in Figure 10 reduce strumming to varing degrees; however their use in reducing the strumming of a long (up to 20,000 feet) flexible cable is probably not practical or economical. Methods shown in Figures 1 through 10 that may offer a practical solution are ribbons, ridges, hair fairing or fringe fairing. Some of the variable parameters for these devices which affect their suppression effectiveness are:

ribbon - type of material
helical or longitudinal application
length
width
spacing
angle of ribbon attachment

ridge - round or rectangular
helical or longitudinal
height or diameter

fringe - type of material
helical or longitudinal
length
spacing

hair - type of material
length

IV. ORGANIZATION

The presentation of existing literature is divided into two sections: (1) Appendix A - Bibliography of Strumming Suppression and (2) Appendix B - Annotated Bibliography of Strumming Suppression literature. Appendix A is an alphabetical listing of all references cited, followed by a listing of U. S. Patents on suppression devices.

Appendix B contains comments and a brief abstract for each reference. The abstract prepared by the author of the reference (indicated by "(Author)" following the citation) was used verbatim when it contained sufficient detail. These were extended when necessary by the writers of the present report.

The three parameters listed for each reference which provide a brief summary of the experimental parameters are:

(1) Reynolds Number Range

(2) Angle of Attack

(3) Type of Device

Although numerous references utilized a "crossflow" Reynolds number defined as,

$$Re = \frac{d\,U\,\sin\phi}{\nu}$$

where d = cylinder diameter

U = free stream velocity

ν = kinematic viscosity of fluid

ϕ = angle of attack

all Reynolds numbers in this report are the freestream Reynolds number defined by, $Re = \frac{d\,U}{\nu}$, to provide a consistent basis for comparison. The angle of attack is defined as the angle between the longitudinal axis of the cylinder and the direction of fluid flow (at 0° the axis is parallel to the flow).

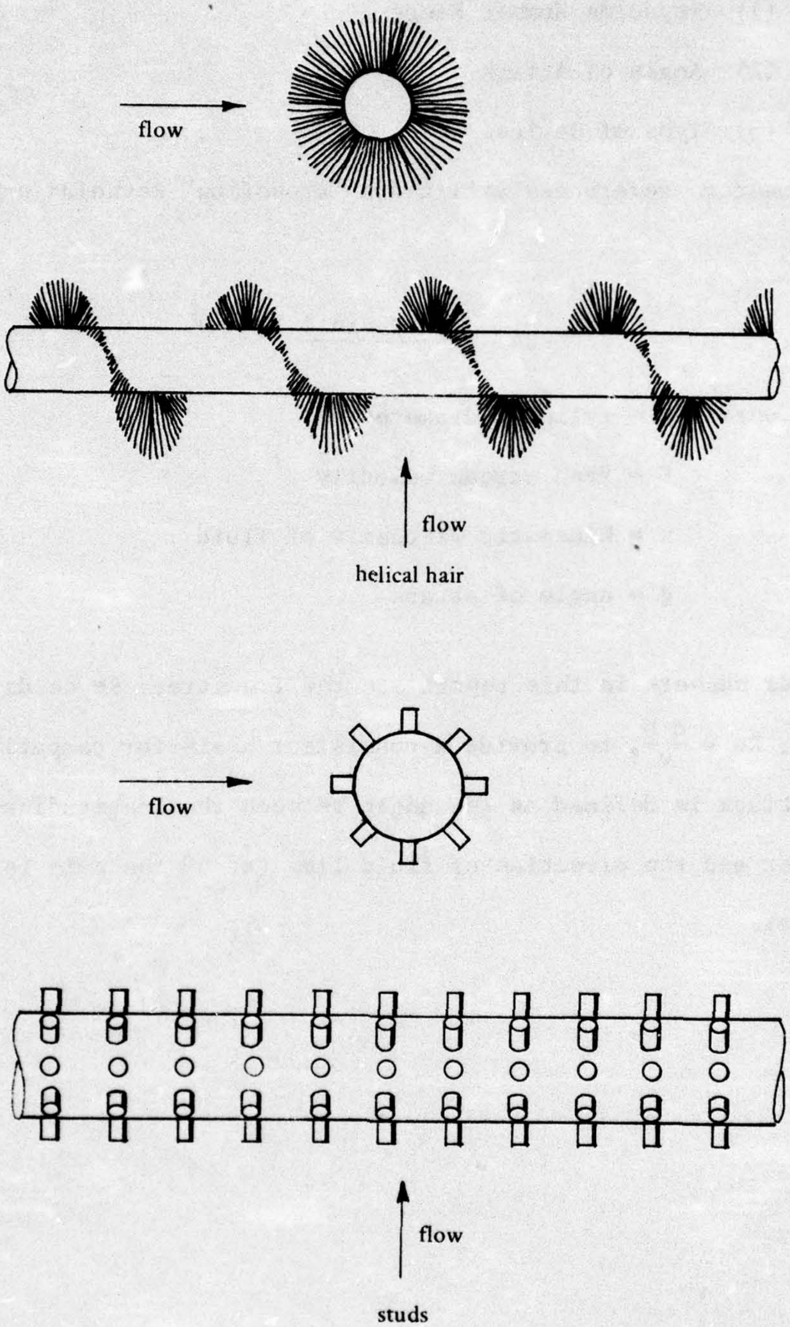
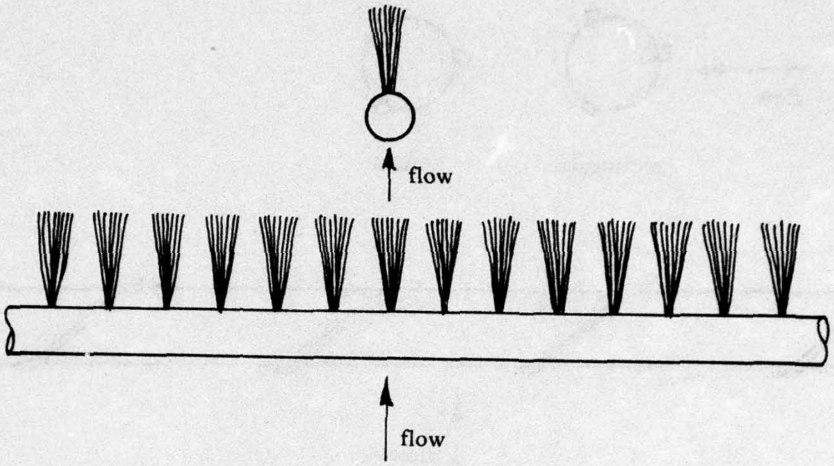
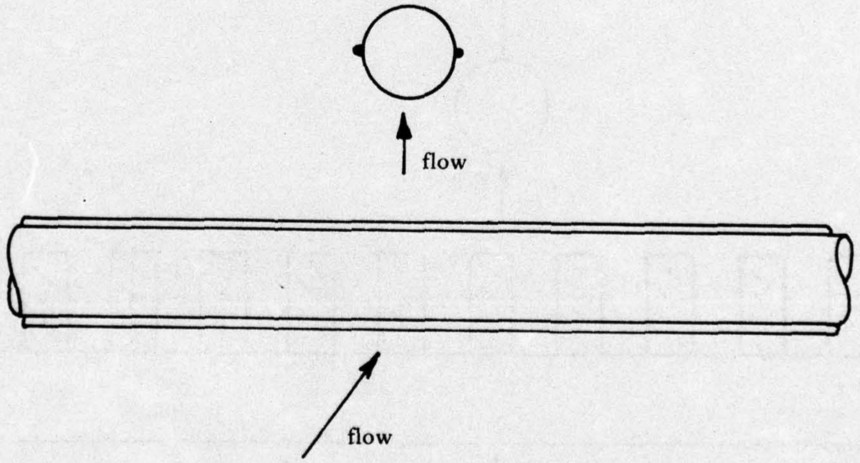


Figure 1.

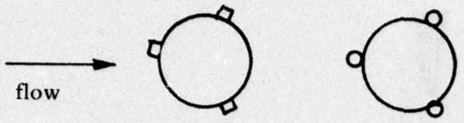


fringe

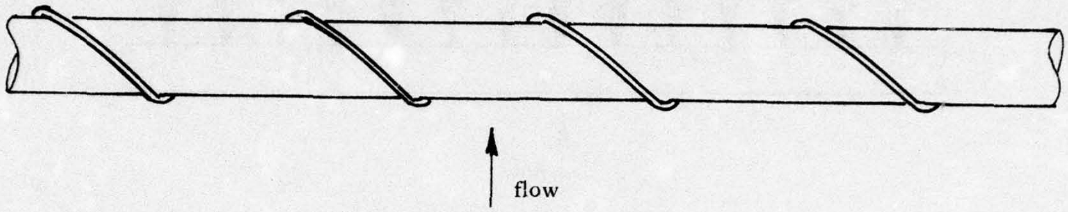


vortex generator

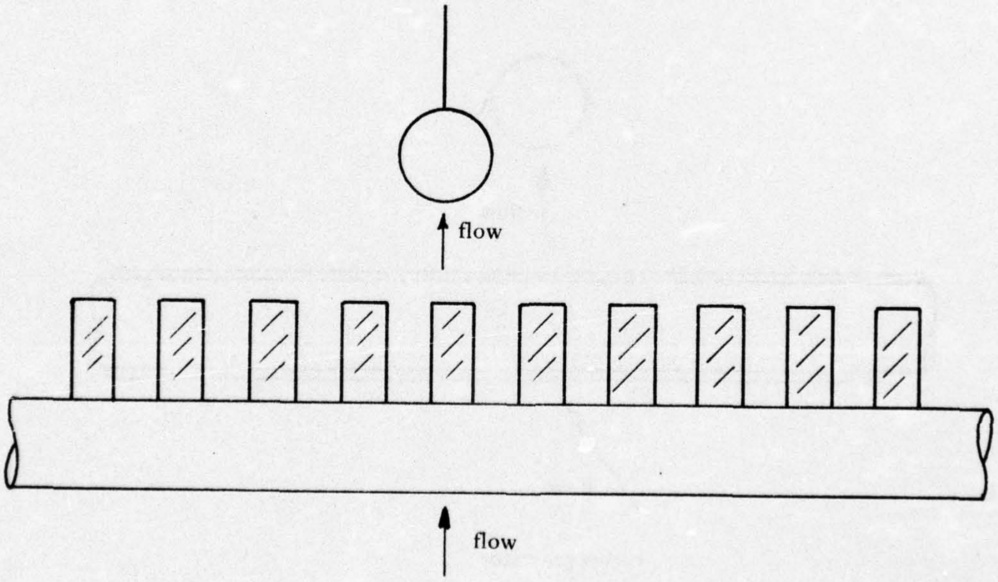
Figure 2.



rectangular round

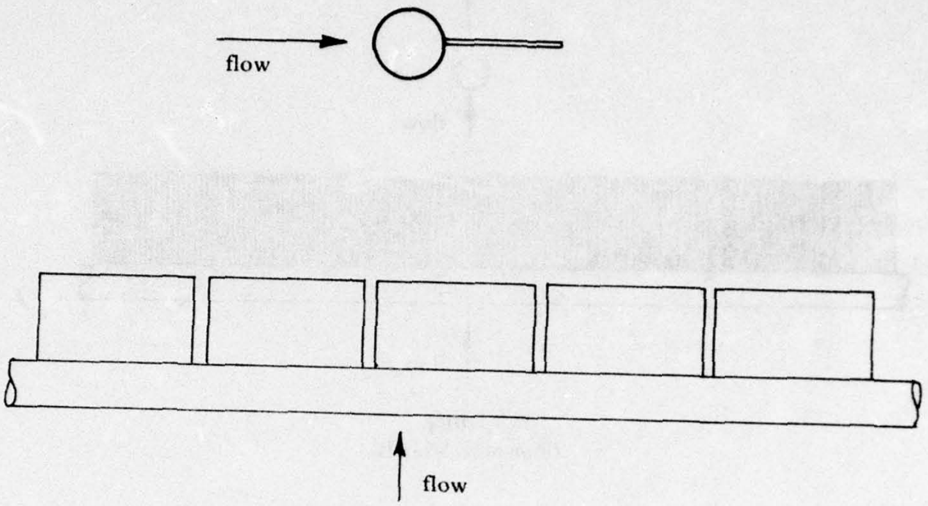


helical strake or ridge

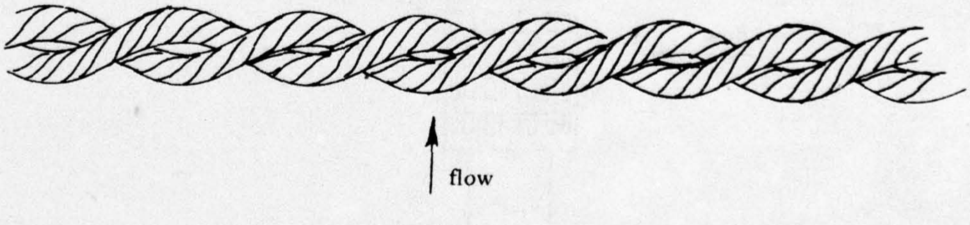


ribbon

Figure 3.

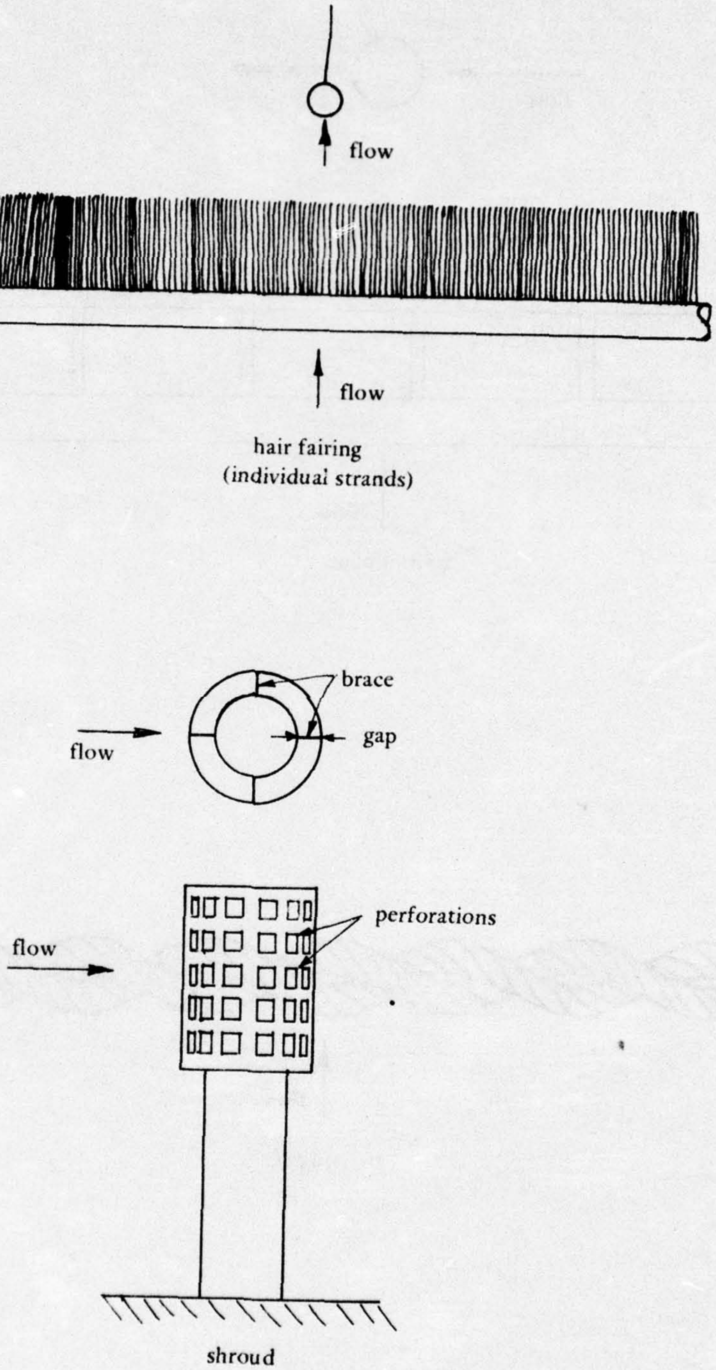


splitter plate



twisted pair

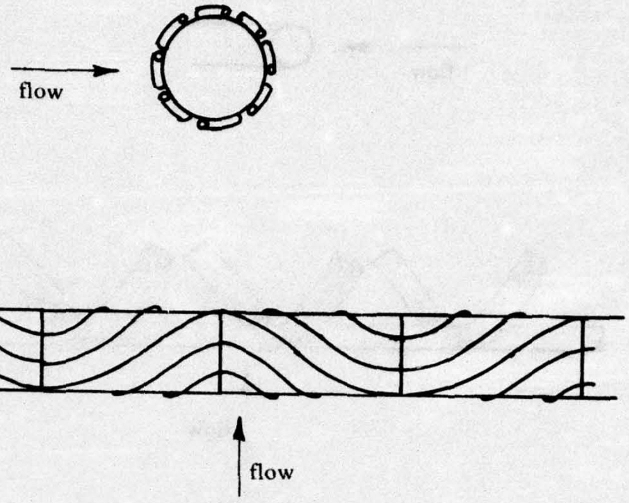
Figure 4.



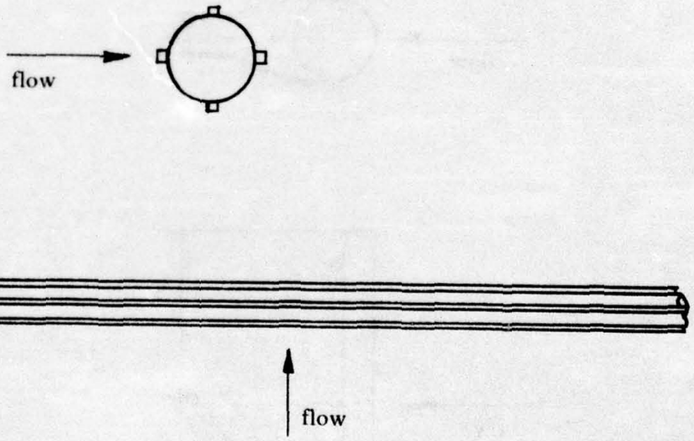
hair fairing
(individual strands)

shroud

Figure 5.

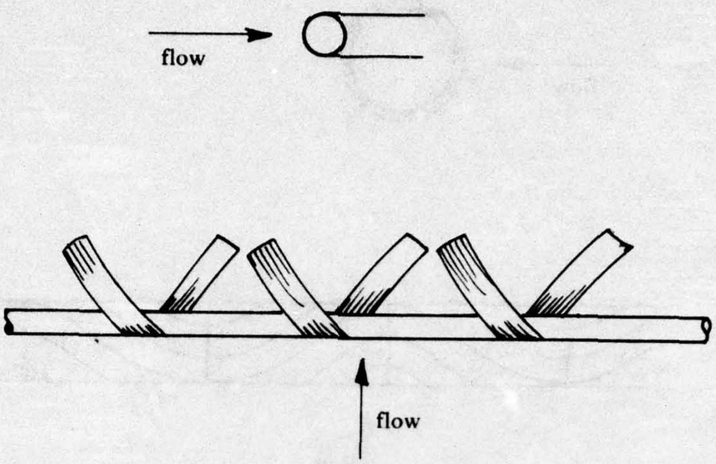


herringbone

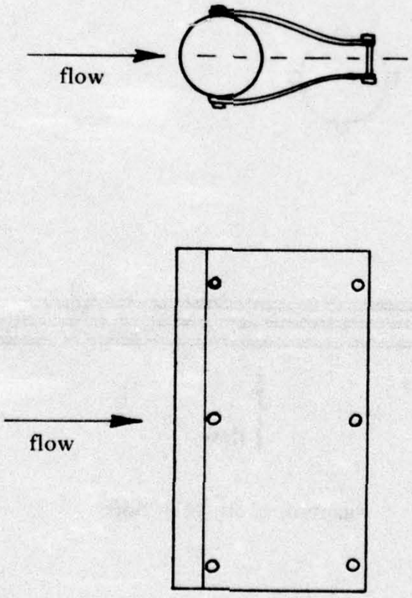


longitudinal strake or ridge

Figure 6.

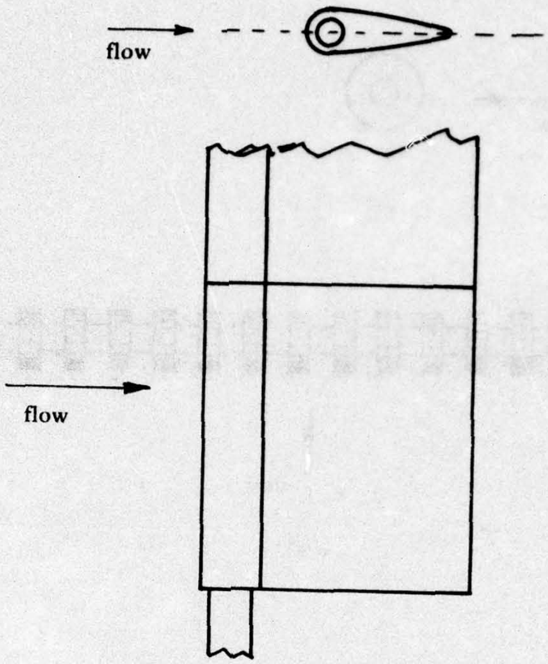


spiral ribbon

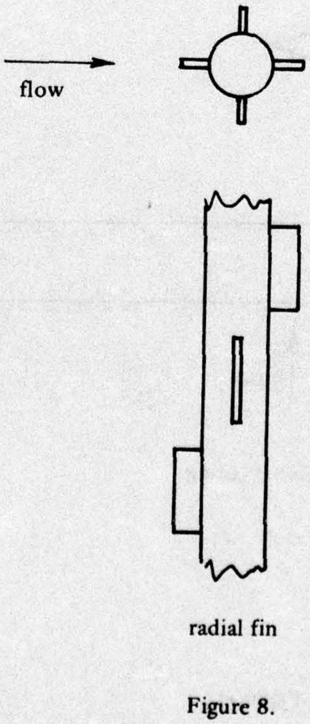


rigid guide vane

Figure 7.

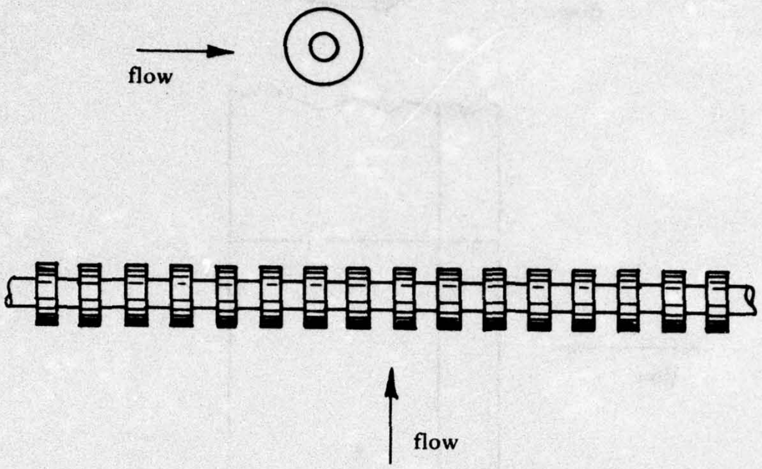


flexnose fairing

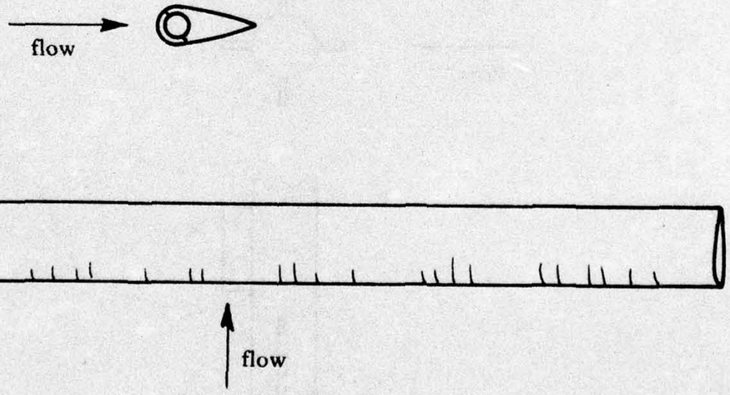


radial fin

Figure 8.

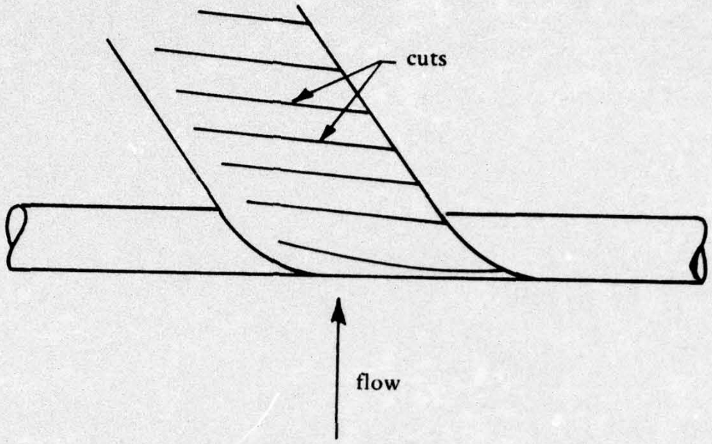


rings

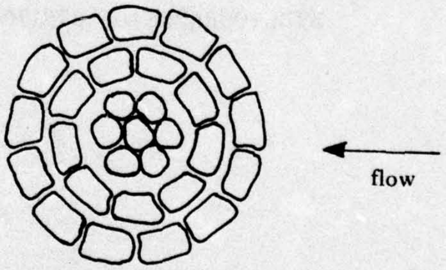


NACA sectional fairing

Figure 9.



helical ribbon



self-damping conductor

Figure 10.

APPENDIX A

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Greber, H., "Device to Prevent Vibration of Aerial Conductors", Patent No. 3,296,357, New York, New York, 1967.

Kelley, R. E. and Lovejoy, R. E., "Paired Cable Drag Reduction with Non-Newtonian Fluids", Patent No. 3,895,595, assignor to the United States of America as represented by the Secretary of the Navy, 1975.

APPENDIX B

ANNOTATED BIBLIOGRAPHY OF STRUMMING SUPPRESSION LITERATURE

Albertsen, N. D., "A Survey of Techniques for the Analysis and Design of Submerged Mooring Systems", Technical Report R-815, Civil Engineering Laboratory, Aug 1974.

Reynolds Number Range: not applicable

Angle of Attack: 90°

Type of Device: twisted cables, hair, antinode splitter plates, streamline fairing

The survey presents a summary of computer analysis of moored cable systems. It is divided into three broad categories: (1) steady analysis, (2) dynamic analysis, and (3) cable strumming analysis and design considerations. Information concerning each analytical technique is presented in tabular form for easy reference and use by the engineer.

All strumming characteristics and drag coefficients were taken from a 1969 report by Dale and Holler. A description of the cable fairing is presented along with performance, Reynolds number, normal drag coefficient and tangential drag coefficient.

Apelt, C. J., West, G. S., and Szewczyk, A. A., "The Effects of Wake Splitter Plates on the Flow Past a Circular Cylinder in the Range $10^4 < Re < 5 \times 10^4$", Journal of Fluid Mech., Vol. 61, Part 1, 1973, pp. 187-198.

Reynolds Number Range: $10^4 < Re < 5 \times 10^4$

Angle of Attack: 90°

Type of Device: splitter plate

Experiments were carried out using models having $L/D \leq 2$ (splitter plate length/cylinder diameter) and the resulting pressure distributions and vortex shedding characteristics are presented. A simple visualization technique which provides explanations of some of the measured results is described.

Tests used rigidly-mounted two-dimensional cylinder models spanning the test-section of a closed-jet water tunnel 8.4 inches in diameter. Pressures at various locations on the cylinder were measured and photos were made of the wake with tracer dye injection. The experiments were primarily to investigate the effects of splitter plates on drag.

It was concluded that splitter plates reduce the drag markedly by stabilizing the separation points, produce a wake narrower than that for a plain cylinder, raise the base pressure by as much as 50% and affect the Strouhal number to a lesser degree. (Author)

Apelt, C. J., and West, G. S., "The Effects of Wake Splitter Plates on Bluff-Body Flow in the Range $10^4 < Re < 5 \times 10^4$. Part 2," Journal of Fluid Mechanics, Vol. 71, Part 1, Nov 1975, pp. 145-160.

Reynolds Number Range: $10^4 < Re < 5 \times 10^4$

Angle of Attack: 90°

Type of Device: splitter plate

The work reported in part 1 has been extended to cover flows past circular cylinders with wake splitter plates having $2 \leq L/D \leq 7$ (length of plate to diameter or characteristic length of bluff body) and to include flows past normal flat plates with splitter plates having $L/D \leq 3.7$. Pressure distributions and wake Strouhal numbers were measured and visualization studies carried out. The results obtained indicate that no further changes would be produced by lengthening the splitter plates beyond the limits tested.

The combined results of parts 1 and 2 provide coherent descriptions of the effects of wake splitter plates for all values of L/D of significance for the two profiles, which are representative of two distinct classes of bluff bodies, viz., those with cross-sections of curvilinear shape for which the flow separation points are not determined uniquely by the geometry and those for which the separation points are fixed.

Short splitter plates in the wake of a circular cylinder very significantly modify the characteristics of the flow past the cylinder. Even though short splitter plates have less effect on the flow past a normal flat plate, the effect is significant even when the splitter plate is very short.

Splitter plates longer than 2D in the wake of a circular cylinder progressively modify the drag and vortex shedding until L/D = 5. For L/D > 5 there is no further change; C_D is constant at 0.8 and vortex shedding from the cylinder is eliminated. However, a vortex street forms well downstream from the cylinder/splitter plate combination.

Splitter plates in the wake of the normal flat plate modify the drag and vortex shedding monotonically as L/D increases from 0 to 3. No further change occurs for L/D > 3; C_D is constant at 1.84 and vortex shedding has ceased. (Author)

Baird, R. C., "Wind Induced Vibration of a Pipe-Line Suspension Bridge, and Its Cure", Transactions of the American Society of Civil Engineers, Vol. 77, No. 6, Aug 1955, pp. 797-804.

Reynolds Number Range: not given

Angle of Attack: 90°

Type of Device: splitter plate

The adverse affect of wind-induced vibrations on a pipe-line suspension bridge over the Colorado River near Blythe, California, is discussed. It was determined that the wind was exciting the 0.5, 1.0 and 1.5 wavelength modes. Methods considered to reduce the transverse oscillation of the pipeline were anchoring the midpoint of the pipeline to the river bed, mechanical dampers and aerodynamic dampers. It was determined that an aerodynamic solution was the best for the long term, and wind tunnel experiments concluded that a sawtooth arrangement of splitter vanes eliminated the vibrations. The field installation of this arrangement proved successful in eliminating the flow induced vibrations.

Barrington, E. A., "Acoustic Vibrations in Tubular Exchangers", Chemical Engineering Progress, Vol. 69, No. 7, July 1973, pp. 62-68.

Reynolds Number Range: $1.7 \times 10^5 < Re < 2.0 \times 10^5$

Angle of Attack: 90°

Type of Device: baffles

An approach to suppress acoustic resonance in tubular exchangers is presented. Vortex shedding and acoustic resonance can have a "tuning" effect and noise generation begins if the vortex shedding frequency approaches to within 20% of the acoustic resonance frequency. The method presented to detune the exchanger employs the placement of baffles to modify the characteristic cavity dimension. This approach is not applicable to cable strumming suppression.

Bearman, P. W., "Investigation of the Flow Behind a Two-Dimensional Model with Blunt Trailing Edge and Fitted with Splitter Plate", Journal of Fluid Mechanics, Vol. 21, Part 2, 1965, pp. 241-255.

Reynolds Number Range: $1.4 \times 10^5 < Re < 2.56 \times 10^5$

Angle of Attack: 90°

Type of Device: splitter plate

The flow in the wake of a two-dimensional model with a blunt trailing edge was examined at Reynolds numbers (based on model chord) between 1.4×10^5 and 2.56×10^5. The ratio of total boundary-layer thickness at the trailing edge to model base height was approximately 0.5. Measurements were taken of base pressure and vortex shedding frequency together with traverses of the wake using a hot-wire anemometer. Traverses carried out along the wake showed a peak in the root-mean-square velocity-fluctuation at a distance equal to one base height from the model rear face. The position of the peak is referred to as the position of the fully formed vortex. The investigation was extended to a model fitted with splitter plates up to four base heights long. For each plate tested, a position of the fully formed vortex was found, and its distance from the model base was discovered to be inversely proportional to the base pressure coefficient. The flow about the model with splitter plates is described as being separated into five régimes of flow. (Author)

The base pressure was found to increase for all lengths of splitter plates over that recorded for the bare cylinder. A significant reduction was noted for $l/h \leq 1.0$ (length of the splitter plate to the base height of the model). Although strumming suppression was not directly addressed, vortex formation behind the model was suppressed for $l/h \geq 2.5$.

Berezow, J., and Sallett, D. W., "An Experimental Investigation of Means to Suppress Flutter Motion of Elastically Suspended Cylinders Exposed to Uniform Cross Flow", TR-72-6, Naval Ordnance Laboratory, Feb, 1972.

Reynolds Number Range: $5.2 \times 10^4 < Re < 3.8 \times 10^5$

Angle of Attack: 90° - 88°

Type of Device: helical strakes, studs, herringbone, longitudinal strakes, splitter plate

An elastically supported twenty-one inch diameter, 108-inch long circular cylinder was towed through a test tank at velocities up to 2.2 knots. Tests were made with a bare cylinder and twenty-one surface modifications to the cylinder. Vibration amplitude and tow angle of the cylinder were recorded photographically. The data shows that the vibration amplitude of the bare cylinder was reduced by the application of all surface modifications; however, the most effective surface modification in the subcritical Reynolds number range was not necessarily the most effective in the supercritical flow region. The most effective overall suppressor was a 5/8" nylon rope in a herringbone pattern attached at 45° to the cylinder generators with the rope separated three inches on center.

This work involved the use of a finite cylinder; therefore end effects will contribute to flutter motion and drag on the cylinder.

Berger, E., "Suppression of Vortex Shedding and Turbulence Behind Oscillating Cylinders", The Physics of Fluids Supplement, Boundary Layers and Turbulence, 1967, pp. 5191-5193.

Reynolds Number Range: 77 < Re < 300

Angle of Attack: 90°

Type of Device: forcing oscillator

The laminar Kármán vortex flow in the wake of a cylinder can be suppressed in a certain Reynolds number range, if the cylinder is stimulated to small oscillations in a direction normal to the mean flow either externally by high-frequency fluctuations, or internally by negative feedback of a hot-wire signal picked up in the wake. If suppression is obtained, the transverse mean velocity profiles become deeper in comparison with those of vortex shedding, however the drag is of the same order in both cases. On the other hand the laminar vortex flow can be stabilized and extended to both lower and higher Reynolds numbers, by exciting the cylinder with frequencies, which synchronize the wake fluctuations. (Author)

Tests were made on an oblong cylinder with cylindrical leading and trailing edges at Reynolds numbers from about 77 to 300 in a wind tunnel; however, only for the Reynolds number range of 77 < Re < 80 was suppression of vortex flow achieved.

Blevins, R., "Vortex Induced Vibration of Bare and Ribbon Cables", Unpublished Naval Ships Research and Development Center Document, Carderock, Maryland, September 1971.

Reynolds Number Range: $9 \times 10^3 < Re < 3.8 \times 10^4$

Angle of Attack: 30°, 45°, 60°, 90°

Type of Device: spiraled ribbon

Visual and quantitative measurements were made of vortex induced vibration of bare cables and cables with plastic ribbon attached to the cable strands for a range of geometric and flow parameters. Visual studies show that a flow parallel to the cable longitudinal axis is entrapped in the near wake of a cable inclined to the free stream. Measurements of acceleration amplitude and frequency of cable vibration show that the frequency of vibration of a bare cable may be predicted by a modified Strouhal relation. The amplitude of vortex induced vibration increased with flow velocity and decreased with inclination to the flow. The addition of ribbons to a cable lowers the frequency and amplitude of vibration below that of bare cable (Author).

The optimum ribbon configuration for minimum vibration was determined to be six diameters long, two diameters wide and a spacing of between one and two diameters.

Calkins, D. E., "Faired Towline Hydrodynamics," Journal of Hydronautics, Vol. 4. No. 3, July 1970, pp. 113-119.

Reynolds Number Range: not given

Angle of Attack: 10° - 90°

Type of Device: NASA airfoil

A theoretical analysis for determining the hydrodynamic forces on a faired towline is developed. The analysis requires that the hydrodynamic forces acting on an element of the towline be defined as a function of the towlines local inclination angle to the flow, and of the Reynolds number. These hydrodynamic forces are known as loading functions. The analysis is based on consideration of the boundary layer formed on the airfoil shaped cross section used for the towlines. The Reynolds number effect on the loading functions is derived using momentum theory, and requires that the pressure distribution around the airfoil section be defined. Potential flow theory is used, and gives excellent results when compared with pressure distribution measurements made on models. The theoretical loading functions are compared with model data obtained from water channel, tow tank, and wind-tunnel tests. The analytical results show excellent correlation with the data. The analysis has been termed Boundary-Layer Loading Functions (BLLF). (Author)

Chey, Y. H., "Strum and Drag Measurements of Underwater Cables", TM 990-2014, General Electric Company, Jun 1975.

Reynolds Number Range: $3217 < Re < 6435$

Angle of Attack: 60°, 90°

Type of Device: fringe fairing, helical strake, helical fringe fairing

A hydrodynamic study was conducted in the towing basin at DTNSRDC to determine the strum and drag behavior of underwater cables. The magnitude of the vertical and horizontal acceleration amplitudes and the normal and tangential drag were compared to those of a bare cable for cables with a wire helix wrap, hair helix wrap and two types of fringe fairing. Tow angle and cable tension were varied. The fringe fairing significantly reduced the acceleration amplitude for the fundamental mode of vibration as well as the second and third harmonics. The wire helix wrap had a normal drag coefficient approximately that as noted for the bare cable, but its strum suppression was not as effective as the fringe fairing. The normal drag coefficient for the fringe fairing and helical fringe was about 1.5 to 2 times that of the bare cable.

Cohen, S. H., "The Hydrodynamic Behavior of a Streamer Type Faired Cable in Various Flows", Thesis presented to the Massachusetts Institute of Technology, Cambridge, Massachusetts, in 1975 in partial fulfillment of the requirements for the degree of Master of Science.

Reynolds Number Range: $1.8 \times 10^3 < Re < 5.4 \times 10^4$

Angle of Attack: 90°

Type of Device: fringe fairing

An experimental investigation of the hydrodynamic forces associated with a streamer type faired cable was conducted in a recirculating water tunnel located at MIT.

The experiment involves a model of the cable mounted as a rigid vertical cantilever in the flow stream of the MIT circulating water tunnel. The drag, lift and moment on the model are measured for each angle the model is rotated about its longitudinal axis while the flow velocity is held constant. These measurements are repeated at intervals of velocity from 0.54 to 15.75 feet per second. The frequency and amplitude of vibration are also measured when the model strums. (Author)

The coefficient of drag for the faired cable was found to be slightly higher than that for a bare cable at all velocities. Within the velocity range where strumming was significant the faired cable reduced the amplitude of vibration from 33% to 77% depending on the velocity of the flow.

Cowdrey, C. F., and Lawes, J. A., "Drag Measurements at High Reynolds Numbers of a Circular Cylinder Fitted with Three Helical Strakes", NPL/Aero/384, National Physical Laboratory, July 1959.

Reynolds Number Range: $8.5 \times 10^4 < Re < 3.8 \times 10^6$

Angle of Attack: 90°

Type of Device: helical strakes

Results are given of measurements of the drag of a circular cylinder with three equally spaced helical strakes in a Compressed Air Tunnel. End plates were used to produce two-dimensional flow over the whole of the model.

The experiments were made for normal flow only with strakes having strake height/diameter ratios of 0.059 and 0.118. The drag coefficient of the cylinder with strakes, based on bare cylinder diameter, became essentially independent of Reynolds number and increased with increasing strake height. If the coefficient was based on the diameter of the circumscribing cylinder, the results were the same and did not differ greatly from the subcritical value for a bare cylinder (i.e., approximately 1.2).

Dale, J. R., McCandless, J. M., and Holler, R. A., "Water Drag Effects of Flow Induced Cable Vibrations", 68-WA/FE-47, American Society of Mechanical Engineers, Dec 1968.

Reynolds Number Range: $300 < Re < 1300$
Angle of Attack: 90°
Type of Device: haired fairing, twisted pairs, splitter plate

This study attempts to determine the water drag characteristics of a smooth circular cylinder due to vortex induced strumming. The drag coefficient for the cylinder was determined at various Reynolds numbers for different diameter cables. An analytical expression was then formulated to determine the strumming cylinder drag coefficient based on an equivalent diameter cylinder. A rule of thumb developed was that cable strumming results in approximately a 35% increase in the drag coefficient.

Of the strumming suppression devices utilized an omnidirectional weather vane fairing reduced the drag coefficient by 60%. The haired fairing drag coefficient ranged from 1.8 to 1.1 for Reynolds numbers of 600 to 1200 respectively.

Dale, J. R., and Holler, R. A., "Spurious Signals from Cable-Suspended Sonar Systems", Journal of Hydronautics, Vol. 3, No. 2, April 1969, pp. 83-87.

Reynolds Number Range: not applicable
Angle of attack: 90°
Type of Device: twisted cables, hair, anti-node splitter plate, streamline fairing

This paper is a consolidation of previous work by the authors. It is intended to provide an overview of the problem of cable strumming--its cause and possible cure. The last section in the paper discusses strumming suppression as follows:

> "The "twisted pair" of cables exhibits a drag reduction of about 30% and attenuates strumming forces by more than 50%. The most effective pitch of the twist was found to be 15 diam. Twisting the pair of wires produces an effect similar to that sought with towers and smokestacks where helical strakes are used to suppress vortex excitation. The "haired streamers" is stable when the hairs are attached to the downstream edge; however, the drag is increased about 20%. The design is omnidirectional if the hairs are attached spirally (spiral pitches up to 9 in. on 0.1-in. diam cables have been effective). The "antinode splitter" cable design is partially effective in reducing strumming when the splitter tabs are

placed at the predicted cable antinodes. An effective tab geometry is 10 diam with the stream and 20 diam along the cable. The "weathervane fairing" consists of streamline omnidirectional tabs. This design is flow-stabilized and reduces the drag almost 50%."

Dale, J. R., Holler, R. A., and Goss, G., "Flow-Excited Underwater Cable Vibrations", Naval Air Development Center.

Reynolds Number Range: not applicable

Angle of Attack: 90°

Type of Device: twisted cables

Provides a brief qualitative background of the mechanism of strumming. A hydrogen bubble flow visualization technique is employed to show the span-wise correlation of the vortex shedding when the cable is vibrating such that the amplitude of vibration is greater than 10% of the cable diameter. Correlation exists only along the length of cable between nodes. Strumming suppression using twisted pairs of cables is mentioned. No quantitative data were presented.

Day, D., and Michailidis, M., "Hydrodynamic Cable Test Facility and Results of Tests on Six Different Cable Fairings and a Bare Cable", National Research Council (Canada), Division of Mechanical Engineers, Report LTR-SH-167, Dec 1974.

Reynolds Number Range: $2.8 \times 10^4 < Re < 5.7 \times 10^4$

Angle of Attack: 90° - 300°

Type of Device: "Flexnose" Fathom Oceanology Ltd.

Six different faired cables and a bare cable were tested at the towing tank facility in the Marine Dynamics and Ship Laboratory of the National Research Council of Canada. The normal and tangential drag coefficients were determined for the cables at velocities of 5.9, 8.9 and 11.8 knots with the angle of the axis of the cables with respect to the flow direction being varied from 90° to 30° in 10° increments. The normal drag coefficient was found to lie within 10% of the $\sin^2 \phi$ relation for a bare cable whereas the tangential coefficient usually peaks at a cable angle of 40° - 50°, and then falls to a value one-half of the peak value at 0°. The drag coefficient at an angle of 90° ranged from 0.12 to 0.89 for the faired cables as compared to a value of 1.04 for the bare wire.

DeGhetto, K., and Long, W., "Dynamic Stability Design of Stacks and Towers", Transactions of the American Society of Mechanical Engineers, Journal of Engineering for Industry, Nov. 1966, pp. 462-466.

Reynolds Number Range: not applicable

Angle of Attack: not applicable

Type of Device: not applicable

A method is outlined for determining the critical wind speed, natural frequency, and approximate maximum amplitude of vibration of tall heater stacks and process towers caused by vortex shedding. Correction procedures reported are: (1) increase diameter to length ratio; (2) addition of an internal gunite or refractory lining; (3) utilization of bracing, guying or frictional dampers; and (4) dynamic spoilers. No experimental data are presented.

Diggs, J. S., "A Survey of Vortex Shedding from Circular Cylinders with Application Toward Towed Arrays", Technical Report No. 122, MAR Inc., Rockville, Maryland, July 1974.

Reynolds Number Range: not applicable
Angle of Attack: variable
Type of Device: splitter plates, ribbons, hair and flag fairings, helical ridges

A survey was conducted to identify the significant advances in the state-of-the-art vortex shedding problem and give a brief historical background of previous research. Emphasis was placed on those theoretical approaches and experimental techniques that are directly applicable to towed arrays. Additionally, the survey contains the results of research efforts to reduce tow cable strum with splitter vanes, ribbons, hair and flag fairings and helical ridges. An extensive bibliography on related research is included in the appendix.

Diggs, J. S., "Hydrodynamic Characterization of Various Towed Array Towcables", Technical Report No. 128, MAR Inc., Rockville, Maryland.

Reynolds Number Range: $6 \times 10^4 - 2.5 \times 10^5$

Angle of Attack: 0° - 20°

Type of Device: helical strake, ribbon

Towing basin and at-sea tests were conducted to determine the normal and tangential drag coefficients for bare cable and cables with a helical strake or ribbon fairing. The hydrodynamic drag characteristics of each cable were evaluated in terms of the measured cable tension gradients, dT/ds, the cable angle, ϕ, and the kite angle ψ using equations derived for three-dimensional towing configurations. Tow angle and kiting were controlled by the tow speed which ranged from 3 - 18 knots. Extensive data comparing the drag coefficients of all the cable configurations are presented as a function of the Reynolds number. The results obtained in the basin were found to correlate with those obtained at sea.

The tangential drag coefficient for a specific tow cable was found to have an empirical relationship with Reynolds number of the form described by Reid and Wilson. The platform towing tension for a cable array system towed at its critical angle can be estimated within 5% when the tangential drag coefficient and tow angle are known.

Doolittle, R. D., "NSRDC Basin Cable Strum Tests", Unpublished Report, MAR Inc., Rockville, Maryland, Jan 1974.

Reynolds Number Range: $Re < 3.4 \times 10^4$

Angle of Attack: 15°

Type of Device: ribbons, helical strakes, hair fairing, lumped masses, rings and collars

Tests were conducted in the NSRDC towing basin to compare tow cable strum reduction techniques through a comparison of the maximum amplitude of the acceleration of the strumming cable and the narrowband acceleration spectra expressed in dB for each run. The techniques investigated included trailing ribbons, helical wraps, fairing bodies, masses, rings and collars. Trailing ribbons were found to suppress strumming as much as 99% depending on their length and width, and a single helical wrap, reversing its spiral at midspan, reduced strumming up to 66%. The reduction of strumming by the other techniques was negligible. No measurements of the drag associated with the trailing ribbon or helical wrap techniques were recorded.

ENDECO, "Hair Fairing", Data Sheet #23, Marion, Massachusetts, May 1975.

Reynolds Number Range: $10^5 < Re < 10^6$

Angle of Attack: varied (towed)

Type of Device: haired fairing

Technical data sheet describing the proprietary product of ENDECO. No experimental data are presented, but the following advantages are claimed: (1) reduction in drag coefficient from 1.2 - 1.4 for unfaired cable to 0.4 - 0.6 at $R = 10^5$ for faired cable; (2) reduction in cable vibration by 20 - 30 dB compared to unfaired cable of the same diameter; (3) faired cable can be winched and sheaved with conventional equipment. Individual "hairs" are polyurethane ribbons about six diameters long, spaced in pairs about 0.5 diameter apart and held on the cable by a metal basket-weave braid. The data sheet indicates that the before-mentioned performance was measured at speeds from 3 to 30 knots.

Etter, R. J., and Huand, T. T., "An Experimental Investigation of the Static Hydrodynamic Characterization of Several Simulated Faired Cables Having Symmetrical NACA Airfoil Sections", Technical Report 530-1, Hydronautics, Inc., Contract No. N123(953)53212A, July 1967.

Reynolds Number Range: $0.5 \times 10^6 < Re < 1.6 \times 10^6$
Angle of Attack: 30° - 90°
Type of Device: NACA airfoil sections

The results of a systematic experimental study of the static hydrodynamic characteristics of several cable fairing models are presented. All models are of symmetrical NACA airfoil sections and vary in maximum thickness from 20 percent to 25 percent. The models were tested with and without the presence of a free surface while angle of yaw was varied from +3° to -5°. In addition, the models were tested at a reduced ambient pressure to produce a nominal cavitation number of 0.366. Photographs of typical cavitation and ventilation patterns are presented and the ventilation characteristics of all models are summarized. (Author)

Vibration data were not measured. Drag and lift coefficients for above tests were presented.

Evans, O. D., "Trial Installation Made to Evaluate Self-damping Conductor", Transmission and Distribution, Vol. 23, No. 3, Mar 1971, pp. 34-35.

Reynolds Number Range: not given

Angle of Attack: ≈90°

Type of Device: self-damping conductor

A self-damping conductor was field tested by Oklahoma Gas & Electric Co. on a 3.7 mile section of a 17.8 mile line. H-frame construction was used with a running span of 800 ft. Vibration recorders were placed on both the self-damping and regular line. A reduction in the peak to peak trace of vibration on a strip chart indicated a 92% reduction in vibration. A recording made with mechanical dampers showed a 84% reduction in vibration. No data are presented.

Fabula, A. G., and Bedore, R. L., "Towing Basin Tests of Cable Strumming Suppression", NUC TN-1188, Naval Undersea Center, San Diego, California, Oct 1973.

Reynolds Number Range: $5.5 \times 10^4 - 8.7 \times 10^4$

Angle of Attack: 5° - 20°

Type of Device: helical ridge

A tow-tank technique of simulating cable strumming vibration and of investigating its suppression has been developed and applied. Twenty-foot lengths of plastic pipe, held under tension and at various yaw angles to the flow, were used with a variety of helical-ridge configurations to investigate the dependence of strumming suppression effectiveness upon ridge configuration. A systematic dependence of effectiveness upon ridge height and helix pitch was found for the 1.31 in. O.D. pipe diameter used. No hydrodynamic benefit of shifting from a single ridge to a triple ridge was detected for the one case tested (a case of medium effectiveness). The results show, as expected, that for equal effectiveness a rectangular (sharp-cornered) ridge will not have to be as high as the round-cornered ridge. Also, as expected, the ridge width/height ratio is not important in the range of practical interest, such as 1 to 2. (Author)

The recommended ridge height to cable diameter ratio for the rectangular ridge ranges from 0.25 to 0.30 and ridge pitch to cable diameter ratio is 20.

Fabula, A. G., and Bedore, R. L., "Tow Basin Tests of Cable Strum Reduction (Second Series)", NUC TN-1379, Naval Undersea Center, San Diego, California, Aug 1974.

Reynolds Number Range: $5 \times 10^4 < Re < 1.75 \times 10^5$

Angle of Attack: 5°, 15°, 25°

Type of Device: helical strakes, ribbons, hair, helical hair, boundary layer trips

The reduction of flow-excited vibrations of tow cables with surface flow control devices was investigated with twenty-foot lengths of 1.31-inch diameter pipe held under tension at angles to the flow of 5° to 25°. Tested cable treatments included flags, ribbons, hair, helical ridges and boundary-layer trips. Pipe vibration and hydrodynamic loads were measured with a pipe-midpoint accelerometer and pipe-end load (tension) cells. Two types of tow tests were made: constant-acceleration runs for coarse surveys of vibrational and hydrodynamic load behavior for the speed range of 4 to 16 fps (2.4 to 9.5 knots), and constant-speed runs at 6, 10 and 14 fps to obtain vibration spectra. Strum reduction effectiveness was judged in two ways: (1) oscilloscope pictures of accelerometer and load cell outputs for the acceleration runs, and (2) spectrum peak line levels of accelerometer and load cell outputs for the constant speed runs. The results show a wide range of strum reduction effectiveness dependent on speed and flow angle. Heavy flags with adequate width and lee-side tie-on hair had outstanding effectiveness. Single helical ridges were mostly moderately effective but ineffective for certain conditions. Lighter flag and various ribbon treatments were moderately effective. Boundary layer trips were only slightly effective and mainly made the vibration more tonal. The hydrodynamic load coefficients vary appreciably with type of strum reduction treatment. The lee-side tie-on hair has appreciably lower normal and axial force coefficients combined with somewhat less strum reduction effectiveness in comparison to the flags of maximum effectiveness. (Author)

Farmer, M. G., "Summary of Langley Wind-Tunnel Studies of Ground Wind Loads on Launch Vehicles", National Aeronautics and Space Administration, Langley Research Center, Paper presented at meeting on Ground Wind Load Problems in Relation to Launch Vehicles, Jun 7-8, 1966.

Reynolds Number Range: 10^6 to 10^7
Angle of Attack: 90°
Type of Device: splitter plate, helical strakes, mechanical dampers

High Reynolds number wind tunnel tests were conducted with Saturn V launch vehicle models equipped with mechanical and aerodynamic dampers. Viscous dampers, tuned viscous damper, electromagnetic dampers, splitter plate, helical strakes and disks were tested to be effective but not enough to totally eliminate the vibration. Trailing cloth in the wake and wire mesh screen around the vehicle as a shroud were found ineffective in vortex suppression. The diameter of the vehicle was 30 feet and the simulated wind speed was as high as 60 knots.

Goldman, R. L., "Karmań Vortex Forces on the Vanguard Rocket", Shock and Vibration Bulletin, Part II, U. S. Naval Research Laboratory, Washington, DC, Dec 1958.

Reynolds Number Range: $1.5 \times 10^5 < Re < 2.5 \times 10^5$

Angle of Attack: 90°

Type of Device: rectangular spoilers

An experimental investigation was conducted to determine an optimum spoiler configuration to suppress the Karmań vortex forces on the Vanguard Rocket. A cylinder was mounted both rigidly and elastically in a wind tunnel to determine the force coefficient and the reduction of the coefficient due to a series of rectangular spoilers mounted in-line with the cylinders axis. For the Reynolds number range investigated, a spiral arrangement of spoilers was found to eliminate the dangers from wind-induced oscillations to the Vanguard.

Grimminger, G., "The Effect of Rigid Guide Vanes on the Vibration and Drag of a Towed Circular Cylinder", David Taylor Model Basin, Bethesda, Maryland, Apr 1945.

Reynolds Number Range: $Re < 3.5 \times 10^4$

Angle of Attack: 90°

Type of Device: rigid guide vanes

The experiments described in this report show that strumming can be reduced or eliminated by attaching a pair of rigid guide vanes, one on each side and extending the length of the cylinder.

The shape of the vanes does not seem important in eliminating vibration; in fact a simple flat plate fin extending along each side of the cylinder is sufficient for this purpose.

However, the drag of the system of cylinder plus guide vanes varies greatly with the shape of the vanes, and is found to depend mainly upon (1) the distance between the trailing edges of the vanes and (2) the angular position of the leading edges of the vanes relative to the axis of the cylinder. With one pair of rigid guide vanes tested, it was possible to reduce the drag of the system to one-half that of the plain cylinder without guide vanes.

The experiments revealed that the drag of a vibrating cylinder is considerably greater than that of a non-vibrating cylinder in the speed range where the amplitude of vibration is a maximum. A simple analysis is given to explain this phenomenon. (Author)

Hays, E. E., Nowak, R. T., and Boutin, P. R., "Strumming Tests on Two Faired Cables", Woods Hole Oceanographic Institution, Woods Hole, Massachusetts, WHOI-75-47, Oct 1975.

Reynolds Number Range: $400 < Re < 8.1 \times 10^3$

Angle of Attack: 90°

Type of Device: ribbon, hair fairing, fringe fairing

Measurements are presented of the transverse accelerations of faired and unfaired cables, suspended in water sixty feet deep with currents up to one knot while under 1000 lbs. tension. Four types of fairing were tested on 3/8" steel double armored wire rope, and one type was tested on 3/4" fibre line. The greatest reduction in strumming was obtained by use of many transverse fibres about eight times as long as the line diameter. (Author)

There is a large spread in the measurement results which limits the use of the data to a general qualitative interpretation.

"The Hydrodynamics Technology of Towed Arrays, FY75", Naval Ship Research and Development Center, Towed Systems Branch, Bethesda, Maryland, Jun 1974.

Reynolds Number Range: not applicable

Angle of Attack: not applicable

Type of Device: not applicable

An outline of the work in the development of the hydromechanic technology of towed arrays during fiscal year 1974 conducted at NSRDC is presented. This format includes a qualitative overview of:

- The contribution to array low frequency self-noise due to array, tow cable and ship motions.
- Tow cable tangential drag and strum suppression.
- The adequacy of array towing geometry algorithms for straight, steady courses.
- The development and validation of an array location and condiguration algorithm for maneuvering tows.
- The characteristics of the ONR Baseline array; the correspondence between vibration and acoustic measurements; array and VIM longitudinal oscillatory characteristics by means of in-basin experiments. (Author)

Proposed future work for fiscal year 1975 is presented.

Johnson, F. W., and Gibbons, T., "Evaluation of USNUSL Sectional Fairing", David Taylor Model Basin, Bethesda, Maryland, Report C-920, Feb 1958.

Reynolds Number Range: $Re < 3.5 \times 10^5$

Angle of Attack: 90°

Type of Device: streamline sectional fairing

Sectional fairings of airfoil cross-section, 6 inches long and 9 inches on chord were towed in a deep water basin at speeds up to 16 knots. The results of a series of tests indicated that the fairing design was not adequate for high speed towing systems due to poor mechanical and material design. Handling difficulty was also expected. Drag coefficients were measured to be in the range of 0.15 to 0.6; vibration was not measured.

Jones, G. W., Jr., and Farmer, M. G., "Wind Tunnel Studies of Ground-Wind Loads on Saturn Launch Vehicles", Journal of Spacecraft and Rockets, Vol. 4, No. 2, Feb 1967, pp. 219-223.

Reynolds Number Range: $2 \times 10^6 < Re < 5 \times 10^6$

Angle of Attack: 90°

Type of Device: disks, helical strakes, splitter plate

Investigations in the Langley Transonic Dynamics Tunnel were made using aeroelastic models of Saturn vehicles with Apollo payloads. Variations with wind velocity, azimuth angle, and structural damping of the bending moments imposed by ground winds were investigated for fueled and unfueled configurations. The results indicate that the unmodified, unfueled Saturn IB and Saturn V vehicles have loads which, at certain wind velocities and azimuth angles, exceed the design bending moments. It was found that these excessive loads may be reduced to acceptable levels by increasing the structural damping to about 3% of critical. Aerodynamic fixes were investigated which tended to alleviate the loads for some of the critical wind velocities and azimuth angles. (Author)

Further full-scale ground wind tests to evaluate the data were planned for a future date. Information applicable to cable strumming suppression is not present.

Joubert, P. N., and Hoffman, E. R., "Drag of a Circular Cylinder with Vortex Generators", Royal Aeronautical Society, Vol. 66, Jul 1962, pp. 456-457.

Reynolds Number Range: $6.4 \times 10^4 < Re < 5.7 \times 10^5$

Angle of Attack: 90°

Type of Device: vortex generator

Tests were conducted in a low speed wind tunnel to determine the effect on the drag of a smooth circular cylinder, due to placing of vortex generators on the cylinder. The generators were 1.2 times the height of the boundary layer, and were placed at 50° from the forward stagnation point. Data show that below a Reynolds number of 3×10^5 the drag coefficient is reduced and above this Reynolds number the drag coefficient is increased. A maximum reduction of the drag coefficient of 71% occurs at $Re = 1.7 \times 10^5$.

The drag coefficient was also determined at varying vortex generator positions at a Reynolds number of 1.3×10^5. A position of 50° from the front stagnation point was found to minimize the drag coefficient.

Kan, I., "Cable Strumming Experiments", Massachusetts Institute of Technology, Cambridge, Massachusetts, Jul 1975.

Reynolds Number Range: $360 < Re < 6850$

Angle of Attack: 90°

Type of Device: helical hair

A study of cable strumming of faired and unfaired cables was conducted in Holbrook Cove along the coast of Maine. Seventy-five foot cables were extended horizontally along a sand bar which was periodically covered by the incoming tide. The cable was instrumented for both accelerometer readings and direct readings of cable vibration amplitude. The single faired cable tested reduced the Strouhal number to 0.12 to 0.13, and reduced the amplitude of vibration by 30%. All of the data collected have not been reduced to date, and a second report is expected in the spring of 1976.

This reduction in Strouhal number was due to the change in vibrational frequency of the faired cable. An example cited in the study at a velocity of 0.57 meters/second shows the frequency of the faired cable to be 18 hertz as compared to the bare cable frequency of 25 hertz.

Kelly, R. E., and Goff, C. N., "Drag and Vibration of Some Wire Ropes and Fairings", Report i-132, U. S. Navy Mine Defense Laboratory, Sep 1967.

Reynolds Number Range: $14{,}500 < Re < 58{,}000$

Angle of Attack: varied (towed)

Type of Device: hair fairing, fringe fairing

The report covers at-sea tests made on bare and faired cable to determine the effect of various modifications on the drag and vibration of the cable. The drag coefficient was a value calculated from the data; however, the vibration was based on visual observations and represents only a qualitative measure.

The haired fairing manufactured by Braincon exhibited the smallest drag coefficient of the fairings tested with a value of 1.32 at a Reynolds number of 6.3×10^4. Visual observations of cable vibration indicated that strumming was negligible for all fairings tested.

Landweber, L., and Grimminger, G., "Lateral Vibration of Circular Cylinder Casued by Motion Through a Fluid", David Taylor Model Basin, Bethesda, Maryland, Report R-326, Apr 1948.

Reynolds Number Range: $Re < 2.5 \times 10^5$
Angle of Attack: 90°
Type of Device: boundary layer trip

The phenomenon of the lateral vibration of circular cylinders normal to a stream was investigated experimentally. A smooth cylinder, clamped at one end, in a vertical position, was towed at various speeds and the amplitude and frequency of its vibration were measured. The effect on the vibration of disturbing the boundary layer by means of fine wires soldered vertically along the surface of the cylinder was also investigated. It was found that the peak vibration occurred at resonance, when the eddy frequency was approximately equal to the natural frequency of the clamped cylinder. The effect of a generator wire having a diameter equal to the thickness of the boundary layer placed at 60 degrees from the front stagnation point caused resonance to occur at a lower speed and reduced the amplitude of the vibration to one half of its bare cylinder value. (Author)

Payne, P. R., "On Reducing the Critical Reynolds Number of a Yawed Cylinder or Cable", Working Paper No. 118-8, Payne Inc., Annapolis, Maryland, Jan 1974.

Reynolds Number Range: 2.5×10^4
Angle of Attack: varied
Type of Device: vortex generator

A cable surface treatment is described in this paper which eliminates the coherent periodicity of the boundary layer separation of normal Reynolds numbers above about 10^4, and hence eliminates the vibration attributable to it. This is achieved by winding a fine wire around the cable, or by cutting shallow grooves in its surface. The wire rings or grooves are essentially normal to the cable axis, rather than parallel to it. They are effective in triggering the laminar boundary layer into turbulence because, when the cable is at an angle to the flow, the boundary layer tends to flow more along its length than across it. (Author)

The approach described in the paper is aimed primarily at higher speeds and shallow angles appropriate to towed arrays. The objective is to promote early (i.e., lower Reynolds number) boundary layer transition from laminar to turbulent by using relatively small "trip" wires or shallow grooves; no experimental data for these approaches are given, except a normal drag coefficient of 0.65 at $R = 2.5 \times 10^4$. The paper suggests another approach which consists of a stepped cable or collars on the cable.

Price, P., and Thompson, R. W., "Suppression of the Fluid-Induced Vibration of Circular Cylinders", Proceedings, Journal of the Engineering Mechanics Division, American Society of Mechanical Engineers, Vol. 82, No. EM3, Jul 1956, pp. 1030-1 - 1030-22.

Reynolds Number Range: $3 \times 10^3 < Re < 5 \times 10^3$

Angle of Attack: 90°

Type of Device: parallel ridges, helical strakes, perforated shroud, radial fins, collars

An investigation of the vibration of circular cylinders in fluid streams has been made in an effort to evolve a means of suppressing the dangerous, wind induced oscillation of tall steel smokestracks.

Exploratory vibration tests of plain and modified cylinders were made over a wide range of cylinder flexibility at subcritical Reynolds numbers in a water channel. These tests established that the enclosure of a cylinder within a concentric perforated shroud was the most effective vibration suppressor of the profile modifications investigated. Wind tunnel tests proved the shroud to be an effective vibration suppressor at transitional and supercritical Reynolds numbers.

The drag coefficient of the shrouded cylinder was found to be substantially immune to Reynolds number effects in the range explored and the value for a typical configuration was approximately 0.6. (Author)

Rispin, P., "Test Plan to Investigate and Optimize Cable Strum-Suppression Techniques", Towed Systems Branch, Naval Ship Research and Development Center, Bethesda, Maryland, Jul 1973.

Reynolds Number Range: $2 \times 10^3 < Re < 2 \times 10^5$

Angle of Attack: 0° - 30°

Type of Device: ribbon, helical strake, rings

The report outlines a test and evaluation program to be conducted at the Naval Ship Research and Development Center. Each cable configuration is to undergo a series of tests to determine its strum suppression qualities as compared to the strumming produced by a bare cable. The comparison is to be based on the average vibration amplitude of the suppressed and bare cables. Prospective candidates for strumming suppression will be tested at sea aboard the R/V Daniel L. Harris III to obtain the correlation between at-sea and laboratory data.

Roshko, A., "Experiments on the Flow Past a Circular Cylinder at Very High Reynolds Number", Journal of Fluid Mechanics, Vol. 10, 1961, pp. 345-356.

Reynolds Number Range: $10^6 < Re < 10^7$

Angle of Attack: 90°

Type of Device: splitter plate

Measurements of the base pressure, drag coefficient and vortex shedding frequency were made on a large cylinder in a pressurized wind tunnel at very high Reynolds number. A definite vortex shedding frequency was not observed for $2 \times 10^5 < Re < 3.5 \times 10^6$; however, above $Re = 3.5 \times 10^6$ a shedding frequency was observed. The values of base pressure coefficient and drag coefficient confirmed $Re = 3.5 \times 10^6$ to be a transition point from the supercritical area to what Roshko termed the transcritical area. In this transcritical area the drag coefficient remains fairly constant at a value of 0.7. The use of a splitter plate did not affect the values of the coefficients of drag and base pressure in the supercritical area, but it did lower their values in the transcritical area slightly. Vortex shedding was suppressed due to the splitter plate.

Sallett, D. W., "A Method for Stabilizing Cylinders in Fluid Flow", Journal of Hydronautics, Vol. 4, No. 1, Jan 1970.

Reynolds Number Range: 10^5

Angle of Attack: 90°

Type of Device: splitter plate

The stability of a finite circular cylinder in a uniform flow was investigated. An analytical expression was derived which relates the location of vortices, vortex strength, and relative velocity of the vortices to the length of the splitter plate necessary to isolate opposing vortices. Four different assumptions were made to calculate the splitter plate length in an effort to bracket the actual value required and determine which assumption was relevant. Experimental work concluded that for a laminar boundary layer a length of 3 diameters was needed to suppress vibration, and a length of 1.5 diameters was needed when a turbulent boundary layer existed.

Sallett, D. W., "On the Reduction and Prevention of the Fluid Induced Vibrations of Circular Cylinders of Finite Length", Shock and Vibrations Bulletin, Bulletin 42, Part 4, Jan 1972, pp. 215-228.

Reynolds Number Range: $4 \times 10^4 < Re < 2.8 \times 10^5$

Angle of Attack: 90°

Type of Device: splitter plate

A brief review of the potential flow model of a cylinder in a uniform flow with point vortices is presented. Stability criteria for the vortices are presented, and a splitter plate is shown to enhance stability and prevent the familiar Von Kármán vortex street. Experimental data are presented graphically which show that vibrational amplitude of a circular cylinder is reduced from 80% - 95% when a splitter plate three cylinder diameters in length is employed.

Scanlan, R. H., and Wardlaw, R. L., "Reduction of Flow Induced Structural Vibrations", Isolation of Mechanical Structural Vibrations, Impact and Noise, American Society of Mechanical Engineers, AMD, Vol. 1, Sep 1973.

Reynolds Number Range: not applicable

Angle of Attack: not applicable

Type of Device: shrouds, helical strakes, splitter plate, streamlining

A review of the nature, cause and suppression of structural vibrations is made. General conclusions are drawn for suppression devices based on work performed using shrouds, helical strakes, streamline design, splitter plates, and other devices which apply to transmission lines. No data are presented for any suppression device discussed. An extensive list of references is given for the vortex shedding phenomenon.

Scruton, C., and Welshe, D. E. J., "A Means for Avoiding Wind Excited Oscillations of Structures with Circular or Nearly Circular Cross-Section", Report Aero 335, National Physical Laboratory, Teddington, England, Oct 1957.

Reynolds Number Range: not given

Angle of Attack: 90°

Type of Device: helical strakes

An investigation was conducted to determine the effectiveness of a three-start helical strake vortex suppression device attached to a circular cylinder. The height of the strake was varied.

In the tests, the critical wind-speeds were found for various values of the structural damping; observation was also made of the maximum amplitudes attained. In addition the aerodynamic excitation was measured at the wind speed for maximum amplitude, and its variation with amplitude was plotted. Finally, the efficacy of the device was tested on a cantilevered tube which closely represented a full-scale chimney stack. (Author)

There was no indication that the strake system produced galloping instability. The optimum height for a pitch of fifteen cylinder diameters was 0.09 cylinder diameters.

Scruton, C., "Note on a Device for the Suppression of the Vortex-Excited Oscillations of Flexible Structures of Circular or Near-Circular Section, With Special Reference to its Application to Tall Stacks", NPL Aero Note 1012, National Physical Laboratory, Teddington, England, Apr 1963.

Reynolds Number Range: not applicable

Angle of Attack: 90°

Type of Device: helical strake

Past experimental work performed at the National Physical Laboratory utilizing helical strakes to suppress vortex induced motion is discussed. An optimum design for welded steel stacks and columns is a three-start system of rectangular-section strakes of height 0.10 diameters and of pitch about 5 diameters. The system need only be applied to the top third of a flexible cantilever such as a smoke stack. It was also noted that circular-section strakes were not as effective in suppressing the vortex-excitation as were the rectangular section strakes of equal height.

Scruton, C., "On the Wind Excited Oscillations of Stacks, Towers, and Masts", Proceedings, Wind Effects on Buildings and Structures Conference, National Physical Laboratory, Teddington, England, Jun 1963.

Reynolds Number Range: not applicable

Angle of Attack: 90°

Type of Device: shrouds, helical strakes, triangular spoilers

This paper is a discussion of the aerodynamic stability of tall, slender structures. Vortex shedding frequency and the lift due to the von Kármán vortex street are discussed with reference to a cylinder of circular section. Devices for the suppression of vortex excitation discussed are shrouds as adopted by P. Price, triangular-shaped spoilers used by R. C. Baird and helical strakes suggested by C. Scruton and D. E. J. Walshe. Several case studies are presented to show how instability was eliminated. Only past experimental work performed at the National Physical Laboratory is presented.

Votaw, C. W., and Griffin, O. M., "Vortex Shedding from Smooth Cylinders and Stranded Cables", Transactions of the American Society of Mechanical Engineers, Journal of Basic Engineering, Vol. 93, Sep 1971, pp. 457-460.

Reynolds Number Range: $240 < Re < 500$

Angle of Attack: 90°

Type of Device: none

A wind tunnel investigation was made to determine vortex shedding frequency and region of formation for a smooth cylinder and four stranded cables. The outer diameter of all test specimens was the same. The cable lay angle varied depending on the number of strands. The results of the experiments indicate that there is little difference in shedding frequency for smooth and stranded cables, so long as either the helix angle or the ratio of strand and total diameters of the cable remain small.

Likewise, the wake formation processes, evidenced by the vortex formation and near wake fluctuating velocities, were not appreciably affected by the different cable strandings investigated. The small vortex formation region behind the vibrating cable indicates increased drag due to the transverse motion, and the increase in drag is very much the same for both smooth and stranded cables. Therefore it is possible, under appropriate circumstances, to use smooth cylinder data to determine the parameters for flow about stranded cables. (Author)

Walshe, D. E. J., "The Influence of Wind Inclination on the Effectiveness of Strakes in Suppressing Wind Excited Oscillations of Cylinders of Circular Section", NPL/Aero/1007, National Physical Laboratory, Teddington, England, Jan 1963.

Reynolds Number Range: $1.2 \times 10^5 < Re < 5.8 \times 10^5$
Angle of Attack: 90° - 20°
Type of Device: three-start helical strake

Wind tunnel tests were made on a cylinder model fitted with three-start helical strakes on a 33° pitch with a strake height to cylinder diameter ratio of 0.125. A bare cylinder was also tested to provide a comparison. The cylinders were mounted on springs and were free to oscillate. The maximum amplitude allowed by the suspension was 0.38 cylinder diameters. The amplitude of oscillation of the bare cylinder for all angles tested reached the maximum allowed by the system, but the strakes tested were found to reduce the amplitude of the oscillations to at most 0.09 diameters at all angles tested.

Walshe, D. E. J., "Wind-Tunnel Investigations of the Dynamic Behavior of Some Tall Stacks and Gas-Turbine Exhaust Towers", NPL/Aero/1263, National Physical Laboratory, Teddington, England, 1968.

Reynolds Number Range: $\approx 10^5$

Angle of Attack: 90°

Type of Devices: shroud

The modelling of chimney stacks for wind-tunnel investigations is discussed and the results of four such investigations are summarized. It is shown that the aerodynamic excitation of multi-flue stacks with exposed flues is dependent upon the flue spacing and that the excitation can be reduced by the three-start helical strake system hitherto used on single cylinders. Other tests indicate that excitation can also be substantially reduced either by the use of a perforated shroud or by perforating the upper part of supporting outer cylindrical shells. (Author)

Walshe, D. E. J., and Cowdrey, C. F., "The Use of Aerodynamic Stabilizing Strakes on Chimney Stacks Supporting Pipes", NPL/Aero/1310, National Physical Laboratory, Teddington, England, 1970.

Reynolds Number Range: $Re < 3 \times 10^4$

Angle of Attack: 90°

Type of Device: helical strakes

Aerodynamic stability tests were carried out on linear-mode models to compare the excitation of a model representing a stack of circular cross-section with that for a stack supporting a small-diameter pipe. The influence of a three-start helical strake system on the instability of the stack was examined. The strake system was placed on only the top one-third of the stack; the pitch to diameter ratio was five, and the strake height to diameter ratio was 0.10. It was found that the presence of the pipe increased the excitation and that this excitation was reduced, but not eliminated, by the strakes.

Walshe, D. E., and Wootton, L. R., "Preventing Wind-Induced Oscillations of Structures of Circular Section", Proceedings, Institute of Civil Engineering, Vol. 47, No. 9, Sep 1970, pp. 1-24.

Reynolds Number Range: not applicable

Angle of Attack: 90°

Type of Device: helical strakes, shrouds

A survey of methods for preventing wind-excited oscillations of structures of circular section is presented. It is shown that there are three main directions in which a solution may be sought. (a) The structure ensures that the critical wind speed for the onset of instability is higher than the maximum expected wind speed; the critical wind speed is proportional to the product of the natural frequency and the diameter of the structure, and therefore may be increased by an increase in one or both parameters. (b) Response of the structure to the aerodynamic forces is minimized by increasing the mass and/or the damping of the structure; several types of mechanical and structural dampers are available. (c) Section shape is altered by fitting strakes or shrouds so as to reduce the periodic aerodynamic forces; a number of other devices are available for directional flows. The criteria for vortex-excited instability and the effect of aerodynamic spoilers on the steady wind loads and on the dispersal of the effluent from chimney stacks are discussed in the Appendices. (Author)

Dimensional sizing of strakes and shrouds is presented in terms of the diameter of the model cylinder.

Walton, C. O., and Merriam, M. M., "Vibration and Towing Characteristics of Surface-Suspended Hydrophone Systems", Report 1558, David Taylor Model Basin, Naval Ship Research and Development Center, Bethesda, Maryland, Aug 1961.

Reynolds Number Range: $2 \times 10^3 < Re < 5.5 \times 10^4$

Angle of Attack: variable--towed

Type of Device: streamline plastic tubing

An experimental program was established under the Fundamental Hydromechanics Program at the David Taylor Model Basin to study the cause and effects of flow-created problems as they pertain to typical surface-suspended hydrophone systems. The specific objectives of the program were: to investigate the capabilities of such systems with regard to speed, depth, and steadiness of tow; to determine how well the behavior of full-scale systems can be predicted for a range of operable conditions; and to provide information which is required to accurately define the configuration of a given system.

This investigation was conducted in three phases.

1. Shallow-water towing tests to determine the magnitudes and sources of vibrations or low-frequency noise components in the acoustic system,

2. Open-water tests to determine the effects of cable scope and fairing in the reduction of vibrations and to obtain information relative to the towing attitude of the system, and

3. Evaluation tests at sea to determine the towing behavior and configuration of a proposed system for submarine radiated noise measurements.

It was concluded that:

1. The vibrations of the single cables interfere with acoustic measurements in the lower end of the frequency range of interest. In general, bundling a number of cables, thereby increasing the effective size of the cylinder, decreases the frequency of vibration below the range of interest.

2. Fairing hydrophone cables reduces cable vibration, aids in obtaining greater operating depth and speed, and improves the stability of the system. (Author)

Weaver, W., "Wind-Induced Vibrations in Antenna Members", Journal of Engineering Mechanics, American Society of Civil Engineers, Vol. 87, No. EM1, 1961, pp. 141.

Reynolds Number Range: $10^4 < Re < 4 \times 10^5$

Angle of Attack: 90°

Type of Device: helical tubular spoilers

A wind tunnel study was conducted on tubular aluminum circular cylinders to investigate the magnitude of the fluctuating lift for various end conditions and methods of suppressing the lift using helical tubular spoilers. The number, size, pitch and length of the spoilers were varied. The cylinder diameter ranged from 1½ in. to 3 in.

Spoiler tests show that a configuration of four helical windings is most effective in suppressing lift forces. A spoiler diameter of d/16 to d/8 is necessary for good suppression (d is the diameter of the cylinder), and a diameter of 3d/32 reduces the lift forces to a minimum. Although the pitch of windings is an important property of the spoilers, the phenomenon is not particularly sensitive to the pitch. The most effective pitch in the wide range of choice (8 d to 16 d) was determined to be 12 d. (Author)

Welsh, R. I., "The Effectiveness of a Splitter Plate in Reducing Transverse Oscillations of a Finite Circular Cylinder in Turbulent Flow", NUSC Report No. 759, Naval Underwater Systems Center, New London, Connecticut, Sep 1966.

Reynolds Number Range: $4.24 \times 10^5 < Re < 2.16 \times 10^6$

Angle of Attack: 90°

Type of Device: splitter plate

This investigation studied the drag and oscillating lift forces at supercritical Reynolds numbers on a finite length circular cylinder with a length-to-diameter ratio of 1.5. Drag coefficients were computed and compared to those for infinite cylinders and were found to agree fairly well with the results of Delaney and Sorensen. A splitter plate with a chord length equal to one cylinder diameter was placed in three positions behind the cylinder, and drag and lift forces were measured to determine the best plate position for reducing drag and suppressing wake-induced transverse oscillations.

The results of this study indicate that a splitter plate attached very close to the downstream side of a finite cylinder is most effective in reducing both drag coefficient and transverse oscillation. (Author)

Woodgate, L., and Maybrey, J. F. M., "Further Experiments on the Use of Helical Strakes for Avoiding Wind-Excited Oscillations of Structures of Circular or Near Circular Section", NPL/Aero/381, National Physical Laboratory, Teddington, England, Jun 1959.

Reynolds Number Range: not given

Angle of Attack: 90°

Type of Device: helical strakes

The utilization of helical strakes as vibration suppression devices was studied utilizing an aluminum cylinder placed in a wind tunnel. The height, pitch and number of strakes was varied. Comparison of the strakes was made using a non-dimensional damping coefficient. The optimum configuration consisted of a three-strake system with a pitch of about 5 diameters and a height to diameter ratio of 0.09. A reverse helix arrangement was not used, and interruption of the strake did not produce optimum suppression.

Zdravkovich, M. M., "Circular Cylinders Enclosed in Various Shrouds", Paper 71-Vibr-28, American Society of Mechanical Engineers, May 1971.

Reynolds Number Range: $5 \times 10^3 < Re < 1.5 \times 10^5$

Angle of Attack: 90°

Type of Device: shroud

The effect of enclosing a plain circular cylinder within a concentric shroud was studied.

The present work examines a new geometry of the shroud, one made of cylindrical rods parallel to the cylinder axis held in spacers fixed around the cylinder. The author has investigated the effects of varying (a) porosity, (b) shroud to cylinder diameter ratio, and (c) circumferential variation of porosity on the vibrational characteristics and has measured the effects on the mean pressure distribution around the cylinder and shrouds.

An interesting feature is the correlation between the mean pressure distribution around the rear side of the cylinder and the suppressing effectiveness of the particular shroud. A constant pressure distribution behind the cylinder means that the shroud will be ineffective, and a parabolic one indicates the effect of a good shroud. (Author)

An examination of the effect of the shroud on the drag force was not made.

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