reprinted from
Proceedings of the Fourth International Offshore Mechanics and Arctic Engineering Symposium — Volume I
Editor: Jin S. Chung
(Book No. I0185A)

published by
THE AMERICAN SOCIETY OF MECHANICAL ENGINEERS
345 East 47th Street, New York, N.Y. 10017
Printed in U.S.A.

VORTEX-INDUCED VIBRATION AND DRAG COEFFICIENTS OF LONG CABLES SUBJECTED TO SHEARED FLOWS

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ABSTRACT

The vortex-induced vibration response of long cables subjected to vertically sheared flow was investigated in two field experiments. In a typical experiment, a weight was hung over the side of the research vessel by a cable which was instrumented with accelerometers. A typical experiment measured the acceleration response of the cable, the current profile, the tension and angle of inclination at the top of the cable. Total drag force was computed from the tension and angle measurements. Two braided Kevlar cables were tested at various lengths from 100 feet to 9,050 feet.

As a result of these experiments, several important conclusions can be drawn: (1) The wave propagation along the length of the cable was damped, and therefore, under most conditions the cable behaved like an infinite string; (2) Response spectra were quite broad-band, with center frequencies determined by the flow speed in the region of the accelerometer; (3) Single mode lockin was not observed for long cables in the sheared current profile; (4) The average drag coefficient of long cables subjected to sheared flow was considerably lower than observed on short cables in uniform flows; (5) The r.m.s. response was higher in regions of higher current speed.

A new dimensionless parameter is proposed which incorporates the properties of the cable as well as the sheared flow. This parameter is useful in establishing the likelihood that lockin may occur, as well as in estimating the number of modes likely to respond.

INTRODUCTION

Mooring systems, sonobuoy cables, deep sea risers and many other ocean structures are subjected to vortex-induced vibration due to ocean current and waves. In the design of such structures, it is essential to have a clear understanding of the nature of the response characteristics of long cylinders subjected to a non-uniform current profile (sheared flow). However, the accuracy of the response prediction of long cylinders subjected to sheared flows is still inadequate for many engineering purposes.

Past research has emphasized laboratory investigations which due to length limitations allowed only very low modal density (for example, see (1,2). The well separated natural frequencies, typical of these experimental arrangements, promoted the occurrence of lockin, the synchronization of the vortex shedding with the vibration. There have been only a few experiments which simulated a sheared flow (3,4). These have simulated a linear shear flow only, and were also limited to very short lengths, which do not represent realistic ocean conditions. Furthermore, the shear parameter B, which has been commonly used to characterize the experimental conditions, reflects only the properties of the flow and not the structure. To properly include the effect of shear on the response characteristics of cables, the shear parameter must reflect the interaction between incoming flow and the structure. A new shear parameter is proposed.

For very long cables in the ocean, the modal density is very high and a sheared current will provide excitation at many frequencies. Single mode lockin is unlikely if not impossible and the correlation of vortex excited forces between two spatially separated points is very small due to the non-uniform current profile. Very little is known about the response properties and drag coefficients of such cables.

To study this problem, field experiments were conducted in the Arctic Ocean during the summer of 1983, and also at St. Croix during the winter of 1983. The results are reported in this paper.

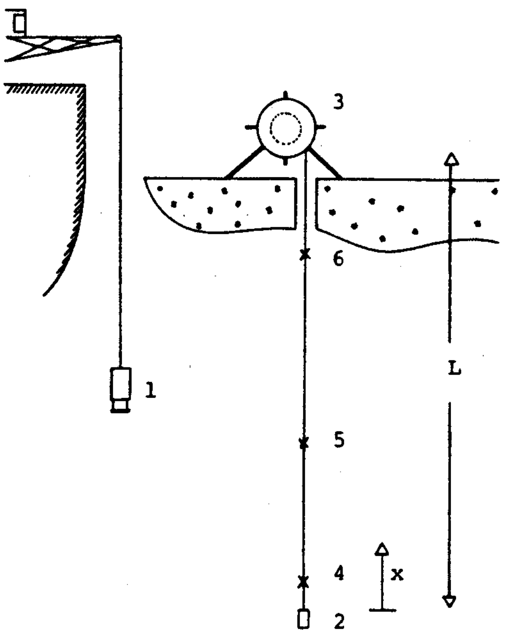
FIELD EXPERIMENTS

The objectives of the field experiments were, (1) to study the response characteristics of long cables in the ocean, (2) to understand the effect of a sheared current profile on the response characteristics, and (3) to investigate the relation between the average drag coefficients and the r.m.s. amplitudes of response of long cables.

Field Experiment in the Arctic Ocean

This field experiment was designed to test the feasibility of acquiring acceptable vibration data on long cables from a floating ship or platform.

In a typical test, a 0.162 inch diameter Kevlar cable (see Table 1) was hung over the side of the Research Vessel Polarstern (operated by the Alfred-Wegner-Institute for Polar Research), or the cable was deployed through a hole in an ice floe. Local ocean current was used to provide the incoming flow to the cable when it was deployed through the ice. When the cable was hung over the side of the ship, the forward speed of the ship and local ocean current were used to excite the cable. Fig. 1 shows a typical experimental set-up, used in the experiments. The test length of the cable was varied from 100 feet to 1,950 feet. Typically 2 or 3



1: Acoustic Current Meter
2: Weight
3: Drum for Cable
4: Built-in Biaxial Acceler. at x = 100 feet
5: Built-in Biaxial Acceler. at x = 600 feet
6: Roving Pair of Acceler.

Figure 1 Experimental Set-Up in The Arctic Ocean

biaxial accelerometers were used to measure the acceleration response of the cable. An acoustic current meter (Neil Brown Instruments, Model DRCM2) was used to measure the current speed at a fixed depth, typically 75 feet below the surface. A weight on the lower end of the cable provided the necessary tension. Weights in water of 17 pounds or 34 pounds were used in these tests. The cable was almost neutrally buoyant and therefore the static tension was essentially constant along the length of the cable.

All the acceleration data were recorded using an F.M. tape recorder (Tandberg, Model T-100). The digitized current meter data were recorded using an audio cassette recorder (Sony, Model BM-12). Fig. 3 shows the data aquisition system for the experiments.

Field Experiment at St. Croix

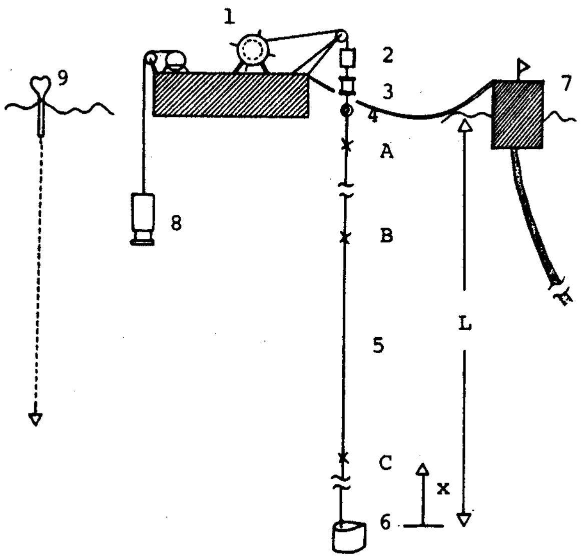
More sophisticated experiments than those completed in the Arctic Ocean were conducted at St. Croix. The principal improvements to the experimental program were as follows:

(1) An inclinometer and a load cell at the top of the cable were used to measure the average drag force on the cables (see Fig. 2),
(2) Continuous current profiles were measured by using XCP's (Expendable Current Profiler, Sippican Ocean Systems, Inc.). A reference current speed was measured by the acoustic current meter (see Fig. 2),
(3) In addition to the 0.162 inch diameter cable, a 0.094 inch diameter cable was tested at lengths of up to 9050 feet (mechanical data in Table 1).
(4) A hydrodynamically faired weight was used to provide the static tension in the cable. The drag coefficient properties of this "fish" were measured in a towing basin prior to departing for St. Croix, so that the effects of drag on the fish could be included in the drag coefficient calculations for the cable. The weight of the fish was adjustable, so that a weight in water, W_o, of 21 to 50 pounds resulted.

The typical experimental set-up can be found in Fig. 2. The data aquisition systems are illustrated in Fig. 3.

Table 1
Specifications of the Kevlar Test Cables

	Kevlar Cable (I)	Kevlar Cable (II)
Maximum Length, Feet, (meters)	2000 feet (609) m	9050 feet (2758) m
Diameter, Inches, (meters)	0.162 inches ($4.11x10^{-3}$ m)	.094 inches ($2.39x10^{-3}$m)
Mass per unit length in air pounds mass/foot (Kg/m)	0.0102 lbm/ft (0.01515 kg/m)	0.00609 lbm/ft (0.00906 kg/m)
Virtual mass per unit length in water pounds mass/foot (Kg/m)	0.02130 lbm/ft (0.03170 kg/m)	0.001022 lbm/ft (0.01521 kg/m)



A: Roving Pair of Biaxial Acceler.
B: Built-in Biaxial Acceler. at x=600 feet
C: Built-in Biaxial Acceler. at x=100 feet
1: Drum for cable
2: Tensiometer
3: Inclinometer
4: Mechanical Low Pass Filter
5: Test cable
6: Hydrofoil Shape Weight
7: Mooring
8: Acoustic Current Meter
9: Expendable Current Profiler

Figure 2 Experimental Set-Up at St. Croix

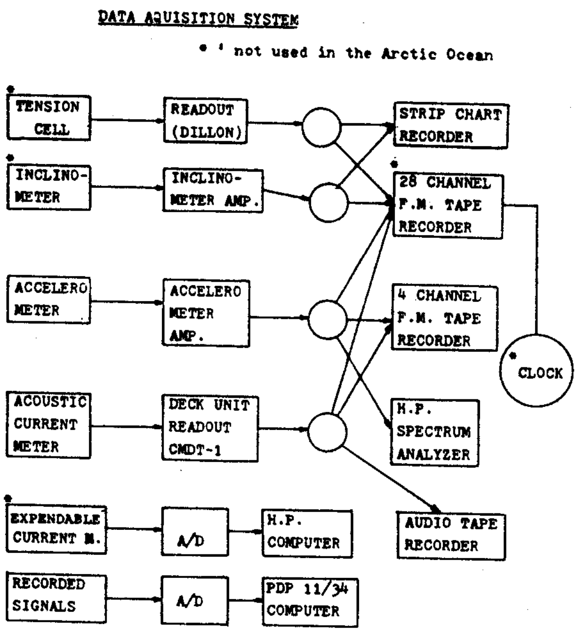


Figure 3 Data Aquisition System

DATA PROCESSING

Acceleration Response

Analog recordings of acceleration response were digitized at M.I.T. using a PDP 11/34 mini computer. Data analysis consisted of a variety of spectral techniques. Only auto-spectral results are presented in this paper. The auto-spectrum of the digitized acceleration signals was defined as follows:

$$S_{\ddot{X}\ddot{X}}(f) = \frac{2}{N_d T} \sum_{k=1}^{N_d} |\ddot{X}_K(f,T)|^2 \qquad (1)$$

where $X_K(f,T)$ is the discrete Fourier transform of the kth segment of the digitized acceleration signals of x(t) and with segment record length T=2 seconds. The total record length was Nd*T, where N_d is the number of averages. For this spectral estimator, the Hanning window was used to reduce the sidelobe leakage(5). The sampling rate was 128 samples per second. 20 averages were used in the auto spectra estimation to reduce bias and random errors(5). A segment length of T=2 seconds was used, resulting in a resolution of 1/T=0.5Hz. The spectra from equation 1 were corrected to account for frequency dependent mass loading of the cables due to the presence of the accelerometers(6).

RESULTS

Response Variation With Depth

Figures 5, 6, and 7 show typical acceleration spectra measured simultaneously at three different locations on the cable. The cable was 0.162 inches in diameter, 950 feet long, and had tension provided by the fish with a weight in water of 21 pounds. The three accelerometer pairs were located at distances of 100, 600, and 875 feet, measured upward from the weight (Figure 4). The current profile for this test is shown in Figure 4, as well as the cable configuration as a function of average drag coefficients.

The current profile was obtained from an expendable probe. Probe outputs give excellent relative measurements of current but need to be matched against an absolute reference current, measured at a specific depth. The reference current in this test was measured at a depth of 95 feet using the acoustic current meter. In hindsight, this proved to be a poor choice of depth, because for this test the measurement from the XCP in the top 100 feet was not useable. The instrument normally gives good readings after a drop of about 15 feet, but not in this case. At 95 feet, the acoustic current meter indicated a steady current of approximately 1.0 feet per second continuing up to the surface at about the same speed as observed during deployment. The XCP trace shows a peak at 70 feet down of nearly 4 feet per second, which was not present on site. An approximate correction to the XCP data is given in the figure for the top 100 feet, and is based on observations made with the acoustic current meter during deployment. The figure itself is then a qualitative measure of the current speed variation. The current direction is also given by the XCP. The current direction varied gradually over the length of the cable, with a total variation of approximately 90 degrees.

The acceleration response spectra give a separate check on the current speed. The principle peak frequency for the top, middle, and bottom locations was 14, 9, and 7 HZ, respectively. Using a Strouhal number of 0.2 this implies current speeds of 0.95, 0.60, and 0.47 feet per second. This corresponds to a maximum Reynolds number of approximately 1280. The water temperature varied from 28°C at the surface to about 16°C, 950 feet down.

At each measurement location there was a biaxial accelerometer, which could measure the transverse vibration of the cable in two orthogonal directions. The absolute orientation of biaxial pair was not known, nor could it be controlled. In general, the vibration observed by any single accelerometer resulted from both the in-line and cross-flow excitation. The cross-flow excitation is due to unsteady lift forces, generated by the vortex shedding process and the in-line excitation is a result of unsteady drag forces. Because current direction varies along the cable lift and drag forces vary in direction.

It is known that the unsteady drag forces occur at approximately twice the frequency of the corresponding lift forces. Therefore, measured response spectra, from a randomly oriented accelerometer, typically have two broad peaks. Figure 6 is a good example. The lower frequency peak results from lift force excitation in the vicinity of the accelerometer and the higher frequency peak is due to drag force fluctuations. The total mean square response at any one location must be computed from the vector sum of the two orthogonal acceleration measurements.

A conclusion which can be drawn by inspection of the three acceleration sepctra shown is that the response at the three locations occurs at substantially different frequencies. This is consistently found in all of the data from the tests and is not a result of picking a peculiarly oriented accelerometer.

It is the conclusion of the authors that the current shear as well as a combination of structural and hydrodynamic damping is responsible for the variation in response spectra along the length. At any specific location on a very long cable, the observed response will be dominated by local excitation. Waves which are created in the cable by the vortex shedding process are attenuated as they travel along the cable. If one assumes a linear damping model, then the waves are attenuated exponentially with distance travelled by the factor $e^{-\xi K \Delta X}$, where ξ is an equivalent linear damping ratio. K is the wave number at the particular frequency of interest and ΔX is the distance travelled ($K=2\pi/\lambda=w/c$). After travelling one wavelength the wave is attenuated by the factor $e^{-2\pi\xi}$, which reveals that $2\pi\xi \approx \delta$ the logarithmic decrement per wavelength travelled.

The response spectrum observed at any location results from the superposition of waves which have been excited over the entire length of the cable, attenuated by the distance travelled. For linear damping this results in a local vibration measurement being an exponentially weighted superposition of many waves. The ones generated nearby dominate the response. If the current varies with position as it does in this example, the dominant spectral peaks at any specific location will be biased towards excitation frequencies near the measurement point.

The spectrum shown in Figure 5 has substantial signal as high as 40 Hz. This is likely the result of high peak flow velocities caused by ocean waves on the surface. The surface was only 75 feet from the top accelerometer pair. Wind driven waves of 4 to 6 second period and a few feet in height were always present during the experiment and did excite the top of the cable with high frequency vortex shedding.

Damping and Effective Length

One of the purposes of this paper is to establish the length of a cable required for one to be able to state that the dynamic response is essentially that of an infinite cylinder. This will be the case when the cable extends to either side of the measurement point a sufficient distance that waves which pass the measurement point will decay to insignificant levels by the time they reach the ends of the cylinder. This will happen if the cable is long and current shear exists along the cable. If the flow is uniform, lockin may result, even on very long cables. Given a sheared current, lockin will not result, and the length of cable required to exhibit the behavior typical of an infinite string will be determined by damping.

Both structural and hydrodynamic sources of damping are important. Hydrodynamic damping is not relevant to lockin vibration. Under lockin conditions the power injected into the cable by the fluid is balanced by the power dissipated internally by the material losses. Under non-lockin conditions, power injected at one location and frequency on the cable may be dissipated back into the fluid at a different position on the cable which is exposed to a different flow velocity. An extreme example would be a region of zero flow velocity but substantial vibration amplitude. Waves travelling through such a region will be attenuated by both material and fluid damping. The effects of fluid damping was apparent in the St. Croix tests and will be discussed in this paper. First, it is necessary to establish the amount of material damping in the test cable.

In air damping values for the test cable were measured in the laboratory on two separate occasions. The first on a dry sample 53.75 inches in length, a tension of approximately 38 pounds and at a measured first natural frequency of 38 Hz. The second was on a sample 8.5 feet long, a tension of approximately 20 pounds and a natural frequency of 14.8 Hz. Repeated tests on both samples revealed the damping ratio to be 0.16% ± .02. This represents an upper bound structural damping value because it includes losses to the air and to the end supports. Such a low value of damping is too small to explain the response spectra shown in Figures 5, 6, and 7.

The attenuation of waves travelling down the cable from the top to the middle accelerometer positions can be estimated by evaluating the total attenuation of response energy of the high frequency vibration which is only generated in the top 100 feet and propagated downward. Figure 8 shows the total vector response spectrum for the top and middle locations plotted on a decibel scale. The total spectrum was obtained by summing the spectra of each

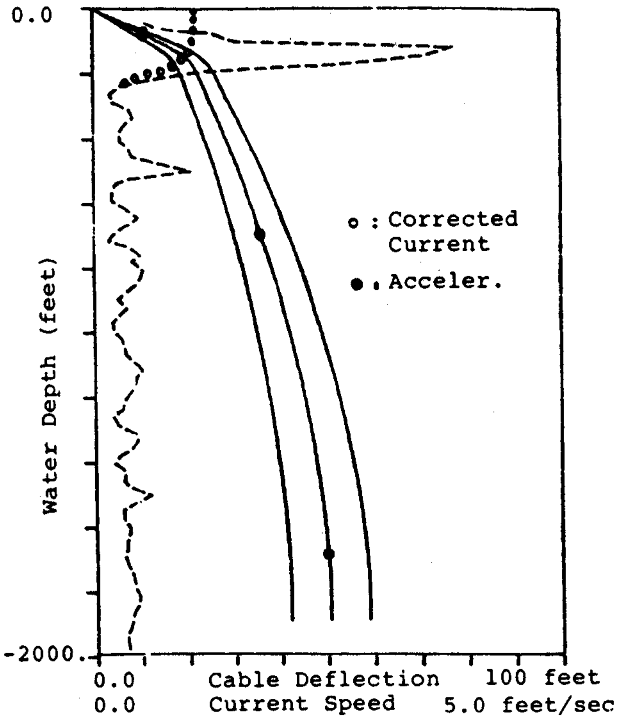


Figure 4 Current Profile, Cable Configurations and Accelerometer Locations

accelerometer in the biaxial pair. The current speed was approximately 1.0 feet/sec at and above the top accelerometer, which was 75 feet below the surface. Below the top accelerometer pair the current dropped off quickly within the next 25 to 50 feet. 275 feet away the speed was approximately 0.6 feet/sec. The areas under the two spectra shown in Figure 8, between 12 and 20 Hz differ by a ratio of approximately 50 to 1. If one assumes all of this was composed of waves travelling downward toward the middle accelerometer, then the energy was reduced by a factor of 50(-17dB) by the time it reached the middle position. The decay of energy in a linearly damped travelling wave is governed by the factor $e^{-2\xi K\Delta X}$. Letting ΔX=275 feet and choosing an average frequency of 16Hz the effective damping can be found from

$$e^{-2\xi K\Delta X} = 1/50$$

This yields a value of damping of 1.3%. Even if only 1/2 of the energy was travelling downward, the attenuation would be 25 to 1(-14dB) and the necessary damping would be 0.9%. Either value is far greater than the 0.16% measured in air. The increase in damping must come from hydrodynamic sources.

From these experimental observations, it was concluded that the vibration response behavior of the long cables tested at St. Croix was essentially that of an infinite string. Standing waves, typical of finite string behavior were not observed, except near the terminations, because waves generated at interior points on the cable were attenuated prior to being reflected from the boundaries. In other words, if the cables are much longer than the distance required for significant attenuation to occur, then infinite string behavior results.

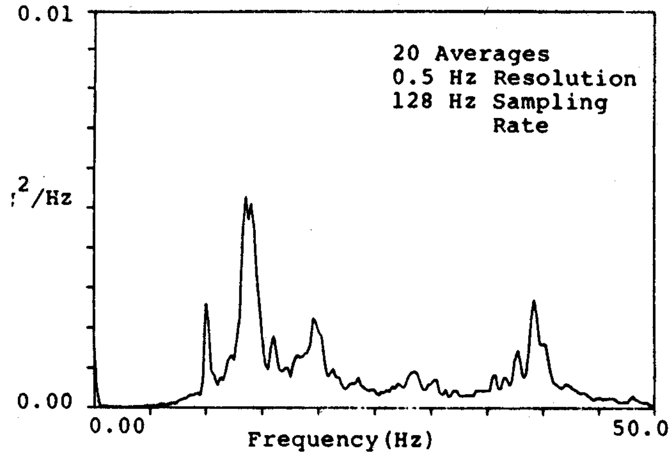


Figure 5 Acceleration Spectrum, x = 875 feet

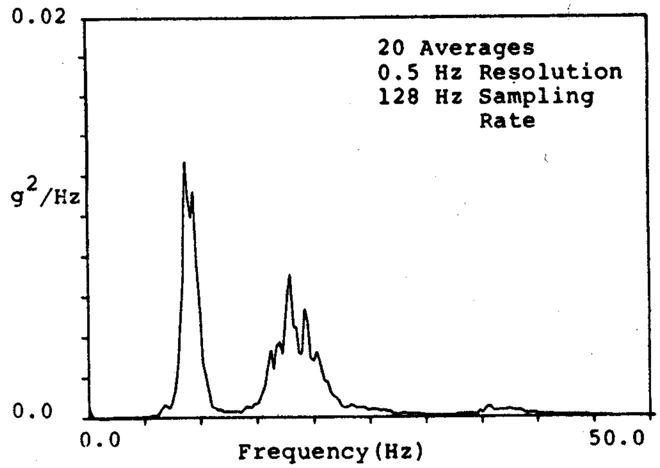


Figure 6 Acceleration Spectrum, x = 600 feet

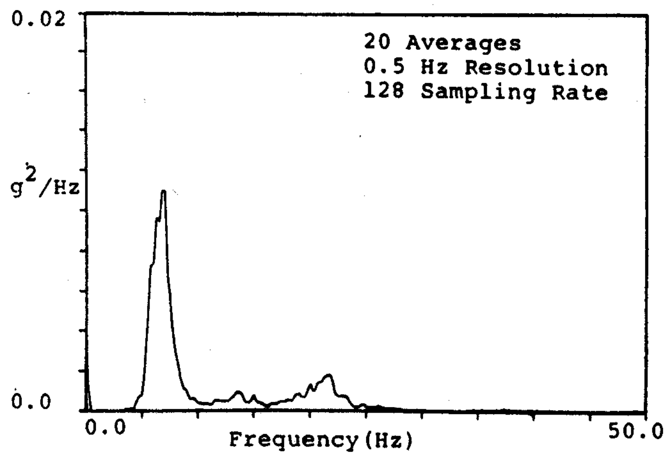


Figure 7 Acceleration Spectrum, x = 100 feet

A non-dimensional parameter, frequently cited as important in the flow induced vibration literature is the length to diameter ratio, L/D. This parameter is of limited importance in characterizing the response of long cables in the ocean. A length scale of much greater significance in establishing the dynamic response of long cables is the length to wavelength ratio L/λ .

From the discussion presented previously a more refined measure of length suggests itself. This is the separation distance required such that the attenuation of energy in waves travelling between two response measurement points is greater than a specified level, such as 90% attenuation. This distance is here defined as the effective length, Le. This effective length is useful in assessing whether or not the cable will act as an infinite string. It is also useful in defining the region around a measurement point which contributes in a significant way to the local response. With this model, the predicted response at any given point is an exponentially weighted response to inputs extending a distance Le to either side of the point. Input outside of this region has insignificant effect on the observed response.

One restriction on the use of this model should be mentioned. This model is applicable under non-lockin conditions in sheared flows, where the fluid exciting forces are uncorrelated along the length. Under uniform flow conditions, lockin may occur and the assumption of the excitation being composed of many independent noise sources is not valid.

Predicting Lockin

It is the opinion of the authors that lockin occurs if and only if the separation of the natural frequencies of the cylinder are large compared to the bandwidth of vortex induced forces. The separation between natural frequencies depends primarily upon the mechanical properties of the system such as mass per unit length, stiffness, tension, and length. The bandwidth of the exciting forces depends on the vortex shedding phenomena and current shear. A measure of the likelihood of lockin is then given by the ratio between the excitation bandwidth due to current shear and the separation in frequency between natural modes. This ratio is in fact, the number of natural frequencies contained within the excitation bandwidth, and is here defined as N_s.

$$N_s = n(f)\Delta f \qquad (3)$$

where Δf is the excitation bandwidth due to current shear.

n(f) is the modal density.

The excitation bandwidth due to shear can be estimated using the Strouhal number and the variation in the velocity over the total length of the cylinder.

$$\Delta F = S_t \frac{\Delta V}{D} \qquad (4)$$

where

ΔV is the maximum velocity difference over the entire cylinder
D is the diameter

S_t is the Strouhal number

For the example of a simple constant tension string, the modal density is constant with frequency and is given by

$$n(f) = 2L/C_p = 1/f_1 \qquad (5)$$

where

L = length of the string
C_p = phase velocity of transverse waves.
f_1 = first natural frequency

Therefore, for the string

$$N_s = S_t \frac{\Delta V}{D} \cdot \frac{2L}{C_p} \qquad (6)$$

If this number is large, lockin will not occur. If it is small, lockin is likely to occur. Two experimental examples are discussed here: the 950 foot long cable described in this paper and the short cable tested at Castine, Maine in 1981.

St. Croix: The velocity variation at St. Croix was essentially 1.0 feet/second. The modal density at a tension of 21 pounds was 10.57 modes per Hz. The phase velocity was 178 feet/second. Letting St=0.2, N_s is found to be 158. Lockin was never observed. Infinite cable behavior was observed.

Castine:
L = 75 feet
D = 1.25 inches
n(f) = 1.0 modes/Hz
ΔV 0.15 ft/sec
St = .2

The maximum current at Castine was approximately 2.5 ft/sec. A spatial variation of approximately ±3% of the flow speed was measured over the length of the test section. This yields a ΔV of approximately 0.15 ft/sec.

For this case

$$N_s = 0.3 \text{ modes.}$$

As a consequence, lockin was frequently observed at Castine. It happened whenever the mean flow velocity resulted in a shedding frequency which coincided closely with a natural frequency. Multimoded non-lockin response did occur when the mean shedding frequency fell between natural frequencies. At these times three or four modes were present in the cross-flow response. The in-line response would at the same time have several modes participating in the response. Under lockin conditions, the excitation bandwidth is very narrow. Under non-lockin conditions, even with very uniform flow the excitation bandwidth broadens substantially. Under such circumstances, the lift force spectrum at every point on the cable is best characterized as a narrow band random process with sufficient bandwidth to excite 2 or more adjacent modes.

Note that Ns approaches zero as the incoming flow becomes uniform. Under uniform flow conditions the bandwidth of the shedding process controls the number of modes participating in the response. Depending on this bandwidth and the location of the mean shedding frequency relative to natural frequencies single mode lockin may happen. When Ns is less than one, the possibility to excite a single natural mode of the cable is very high. Single mode lockin is very likely. If Ns is much larger than one, there is no chance to have lockin response, as more than one mode is always involved in the response. For the St. Croix test Ns was greater than 100, and it was less than one for the Castine experiment.

From this evidence, it can be concluded that the proposed parameter, Ns, can predict the possibility of lockin response, and includes the effects of shear on the response characteristics of the cable.

<u>Measured Drag Coefficients of Long Cables</u>

The averaged drag coefficients were obtained by solving the nonlinear static equations of the cable given below:

$$\frac{dT}{dS} = \mu\sin\phi - 1/2\rho_w C_f \pi D\, V_t|V_t| \quad (7)$$

$$T\frac{d\phi}{dS} = \mu\cos\phi + 1/2\rho_w C_d D\, V_N|V_N| \quad (8)$$

Fig. 9 defines the notation used in this expression. The corresponding boundary conditions are:

T at the top of the cable = measured value
ϕ at the top of the cable = measured value
T at the bottom of the cable = $\sqrt{Do^2 + Wo^2}$
D_o, W_o : drag force and weight in water of the fish, respectively
ϕ at the bottom of the cable = arctan (Do/Wo).

With these boundary conditions, the finite difference form of equation 7 and equation 8 was solved and the corresponding drag coefficient was obtained by iteration, for the measured current profiles. The iteration scheme which was used in this process was 'mid point iteration'.

Five different tests were available in which the 0.162 inch diameter cable was used and current profile data were available. The cable was tested at

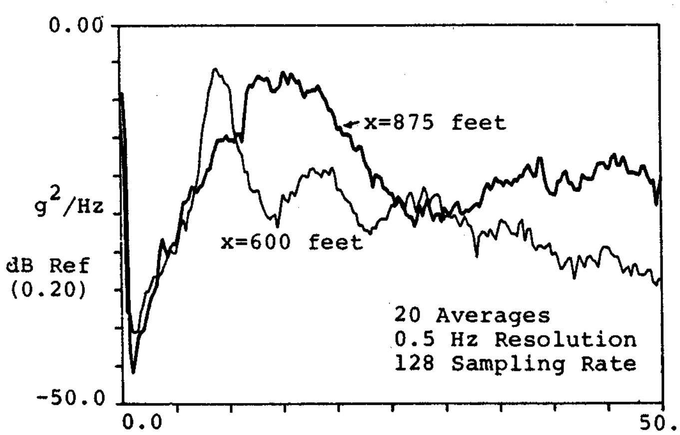


Figure 8 Total Acceleration Spectrum in dB at x=875 feet and 600 feet

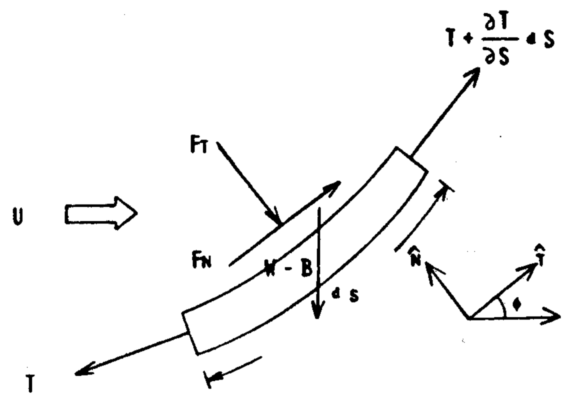
two different lengths, 950 feet and 1950 feet. The average drag coefficient data as determined from the top angle and tension data, and the iteration method described above are presented in Table 2. The current profiles were similar to that of Figure 4 with the maximum current occurring near the surface. The maximum current is also given in the table. The first row in the table corresponds to the profile shown in Figure 4. Figure 4 also shows equilibrium cable positions for three different trial values of C_D.

Table 2
Average Drag Coefficients
on the 0.162 Inch Diameter Cable

	Length (feet)	Maximum Current (feet/sec)	C_D
1.	950	1.0	1.56
2.	950	0.9	1.48
3.	1950	1.15	1.40
4.	1950	1.4	1.58
5.	1950	0.8	1.45

1 m = 3.281 feet
1 m/s = 3.281 feet/sec

The Reynolds range for all five experiments was from approximately 200 to 2000. The average value of drag coefficient was approximately 1.49. The corresponding rigid cylinder value is approximately 1.0.



$F_n = 1/2\rho_w C_d D U_n|U_n|$
$F_t = 1/2\rho_w C_f \pi D U_t|U_t|$
$U_n = U \sin\phi$
$U_t = U \cos\phi$
$\mu = W\text{-}B$

ρ_w: Density of Water
C_d: Normal Drag Coeff.
C_f: Tangential Drag Coeff.
W : Weight per Unit Length of Cable
B : Buoyancy per Unit Length of Cable

Figure 9 Forces Acting on Cable Segment

The average results given here do not give any insight into the variation of drag coefficient along the cable as a function of response amplitude or Reynolds number. These variations must exist as demonstrated by the recent measurements under lockin conditions at Castine which resulted in drag coefficients which were considerably higher than those of the present average results. Vandiver (8) and McGlothlin (11) reported on experiments in a natural flow channel above a sandbar at the mouth of Holbrook Cove, near Castine, Maine. The tidal currents provided nearly uniform flow over the 75 foot test cable, an instrumented piece of flexible PVC tubing, 1.25 inches in diameter. Data was recorded in the Reynolds number range of 5,800 to

17,000, resulting in measured drag coefficients from 2.4 to 3.2. This is 2.0 to 2.7 times the stationary cylinder values.

Although the present data set does not reveal local drag coefficients, some very significant results were obtained relating local flow velocity to local root mean square displacement response. These results are presented next.

The Relation Between R.M.S. Response and Flow Velocity

One of the most valuable results to come from the St. Croix tests is summarized in Figure 10. This is a plot of total r.m.s. displacement response measured at single points on the cable, versus the local current speed, Reynolds number and peak vibration frequency. Even with substantial scatter, there is a very clear relationship between local current speed and local response amplitude.

The mean square dispacement of the cables was calculated in the frequency domain by double integration:

$$E[X^2(t)] = \int_{f_c}^{\infty} \frac{1}{(2\pi f)^4} S_{\ddot{X}\ddot{X}}(f)\, df \qquad (9)$$

where fc is a cut-off frequency used to avoid noise expansion at near zero frequencies.(6) fc was determined by looking at the auto spectrum of the acceleration signal, Sxx (f), in a dB scale, and choosing the frequency where the spectral amplitude was more than 40 dB down from the principal spectral peak.

Higher velocity regions clearly produced larger response. This is a consequence of the infinite cable behavior. It is shown in Reference 6 that if one assumes a constant mean square lift coefficient acting on a very long cable in a sheared flow, then the local r.m.s. displacement response will be proportional to the square root of the local flow velocity.

Since the drag coefficient is known to be dependent on response amplitude, then understanding the relationship between flow velocity and response amplitude on long cables will lead to the ability to predict local drag coefficients.

Further research in this area should lead to a much better ability to predict the performance of deep water mooring systems.

CONCLUSIONS

- Long cables subjected to sheared flow often behave like infinite strings.
- Single mode lockin was not observed for long cables in sheared current profiles.
- The new parameter defined in equations 3 and 6 is a useful measure of the effect of shear on the vortex-induced vibration of cables. It is especially appropriate in determining the likelihood of the occurrence of lockin.
- The drag coefficients for the long cables in sheared flows were much less than those obtained for short cylinders and cables in uniform flows and lockin conditions.
- To predict the response of long cables subjected to sheared flow, an infinite string formulation may be appropriate rather than the conventional modal analysis which assumes the presence of standing waves along the cables.
- The local root mean square response of a long cable in sheared flow is dominated by local flow conditions. Regions of higher velocity have higher root mean square response.
- Though not yet confirmed by field data local drag coefficients are likely higher in regions of greater root mean square displacement response.
- The effect of shear on the response characteristics of cylindrical structures can be tested for in the laboratory if appropriate values of the parameter N_s are preserved in the model test.

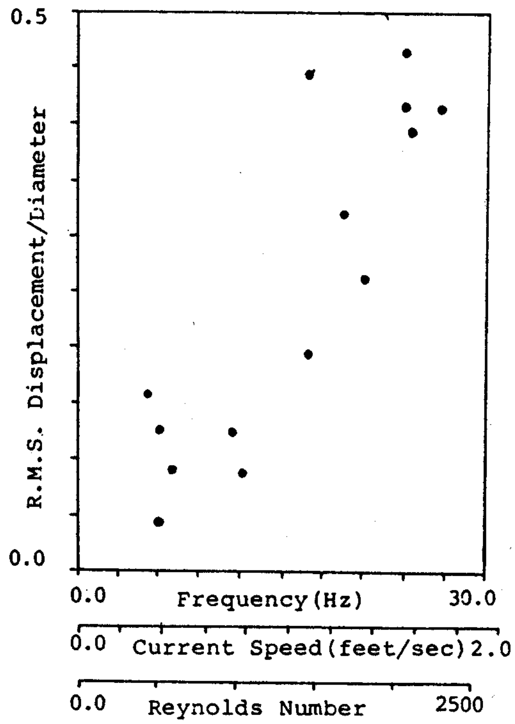


Figure 10 Root Mean Square Displacement Response vs Flow Speed

ACKNOWLEDGEMENTS

This research was sponsored by the Naval Air Development Center in Warminster, Pennsylvania. The field experiments at St. Croix were successful due to the valuable efforts of many individuals: Mr. John Brett and Mr. Frank Marshall of NADC, Mr. Jim Hannon and Mr. Mike Sawchuk of Sippican Corp., Mr. Peter Van Hamm of Sanders Associates Inc., and Mr. Robert Tyger (Master); Mr. Clifford Ives (Engineer) and the crew of the YFN-1126. The authors appreciate their valuable contributions.

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