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A Field Study of Vortex-Excited Vibrations of Marine Cables

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ABSTRACT

A variety of cables were studied under controlled conditions in the ocean. Sections of cable, 76.5 ft in length, were exposed to a spatially uniform, time-varying current. Vibration response, current velocity, and tension were simultaneously recorded. Care was taken to minimize complicating influences, such as lumped masses and nonuniform tensions. The data revealed strong interaction between the vortex shedding process and the natural frequencies of each cable. Under lock-in conditions the spanwise vibration mode shape corresponded correctly with the "locked-in" natural frequency. A cable with an antistrumming fairing was tested simultaneously with an unfaired length of the same cable; the vibration frequencies and amplitudes are compared.

INTRODUCTION

The transverse oscillation of cylinders in a current is a phenomenon that has received much treatment, both theoretical and practical. The fluctuating forces can lead to accelerated fatigue failure of cables or structural members, or to erroneous data collected by moored or towed sensor arrays. Data obtained on full-scale systems have been difficult to interpret due to complications, such as lumped masses or nonuniformity of flow velocity and tension over the length of the test section. Studies on rigid and flexible cylinders (with and without fairings, splitter plates, or the like) have been conducted in wind and water tunnels.[1-7] The data are valid, but the validity of extrapolating from these very short lengths to the behavior of long cables in the field is not certain. Theoretical treatments are not adequate for the prediction of on-site systems. Work is also being done to model cable behavior numerically.[8]

In an attempt to bridge the gap between experimental and theoretical data, a field study was conducted on 76.5-ft lengths of various cables with ends fixed and held under constant tension in a uniform flow. The frequency and amplitude of the cable vibrations were monitored as the current velocity varied over half of a tidal cycle at the test site. The lock-in phenomenon was studied by varying the tension during a period of constant current velocity. This had the effect of changing the cable's natural frequencies, while maintaining a constant preferred Strouhal frequency. It is hoped that data obtained from this intermediate

References and illustrations at end of paper.

size, but manageable, experiment will be of value in relating the results of tunnel studies and complex full-scale experiments. A summary of cables tested and test conditions may be found in Table 1.

THEORETICAL BACKGROUND

A bluff body positioned in a fluid flow will shed vortices. For rigidly mounted cylinders, a pair of vortices will be shed simultaneously for Reynolds numbers up to 40. For higher Reynolds numbers, up to about 10^5, vortices will be shed alternately from each side of the cylinder. The vortex formation is associated with increased local flow speed, and therefore reduced pressure, so that the cylinder experiences a force transverse to the flow. When a vortex is then shed from the opposite side, a force in the other direction is felt. The frequency of this alternate vortex shedding can be found from

$$f = \frac{sv}{d},$$

where s is the Strouhal number, determined experimentally to be 0.21 for rigid cylinders; v and d are the flow velocity and cable diameter, respectively. In addition to the lift, the force has a drag component in line with the flow. Since this is felt identically regardless of which side of the cylinder is shedding the vortex, this fluctuating drag occurs at two times the frequency of the lift force.

Cylinders or cables free to vibrate will also shed vortices alternately in this same Reynolds number range. The shedding occurs at the peaks of the motion, and the cable vibrates at the shedding frequency. This frequency is not as easy to predict as that for a rigid cylinder. The vortex-induced driving force interacts with the natural frequencies of vibration of the flexible system. The amplitude and stability of the motion depend on many factors, such as damping and the relation between the natural frequencies and the frequency at which vibration would occur if vortex shedding alone controlled the motion.

For a taut cable in air, the natural frequencies are given by

$$f = \frac{n}{2L}\sqrt{\frac{T}{\mu}} \quad ,$$

where n is the mode number, and L, T, and μ are the cable length, tension, and linear density, respectively. The natural frequencies are seen to be equally spaced. The shape of a cable vibrating at some mode is given by

$$A \sin \frac{n\pi x}{L}$$

for fixed end conditions. For a cable in water, the linear density must include the added mass, which is a weak function of frequency and which may cause a small change in the spacing of the natural frequencies. In this experiment, the first several natural frequencies were measured directly and were found to agree with the predicted values.

EXPERIMENTAL ARRANGEMENT

In 1974, preliminary tests on long cables were conducted as part of the MIT Ocean Engineering Summer Laboratory.[9] Building on this test experience, a refined experiment was conducted in 1975.

The site of the experiment was a sandbar at the mouth of Holbrook Cove in Castine, Maine. This bar is exposed at low tide and covered by 8 ft of water at high tide. A preliminary current survey determined the direction of flow during rising tide, so that the cable could be oriented normal to the flow. The longest span of uniform current velocity set the limit for cable length. During the course of this tide, the current varied from about 2.4 ft/sec when the water first covered the cable to zero at high tide. A 3-minute traverse of the test length showed no current variation of more than 2.5 percent.

The cable was supported as shown in Fig. 1. Six 10-ft pipes were water-jetted into the sandbar. The outer two at each end were used to take up the tensile load. The inner piles were made to accept removable inserts that held the sheaves over which the test cable was laid. It was necessary to make the aboveground apparatus removable so that the pipes and cables when not in use would not interfere with boat traffic. The cable was supported 20 in. above the sandbar, out of the boundary layer.

A tensiometer (sensitivity 1 v per 100 lb) in line with one end of the cable gave a continuous measure of the tension, which varied somewhat with current speed and creep in the system. A small oscillatory component of the tension, caused by the vibrations, could be measured, but was not felt to be reliable enough to be used as an analytical tool.

At the opposite end of the cable, a hand winch was positioned to control cable tension. The boat containing the recording apparatus was moored at this end of the section, and swimmers could be sent into the water to vary the tension at any time. The signal wires from the instruments ran along a guide rope on the sandbar, and then up to the boat in a group.

Two basic instruments were used to measure the cable vibrations. Commercially available, single-axis accelerometers, with a ± 10-gm range (sensitivity ~ 7 millivolt/gm), were attached to lightweight mounts that could be moved along the cable by a swimmer. Accelerometer traverses were run in order to determine the relative phases and amplitudes between various points on the cable. In this way spatial correlation of cable motion could be measured.

An instrument that measured displacement directly was developed for this experiment (Fig. 2). Termed "the fish," it consists of a rotary potentiometer connected to the cable by a moveable arm. The potentiometer housing provides both waterproofing and a stable platform. Fins provide vertical and lateral stability. When properly trimmed, the neutrally buoyant fish streams behind the cable and remains essentially at rest as the coupling arm, attached to the cable, moves up and down. The varying resistance is used in a simple voltage divider circuit, and gives a sensitivity of 0.66 v/in. deflection. Except at very low frequencies, less than 4 Hz, when friction in the seal caused the fish to follow the cable motion, this device proved to be a reliable tool. Its output is directly proportional to the vibration amplitude of the cable, making data interpretation easier than with accelerometers.

Current measurements were made by an electromagnetic current meter with a sensitivity of 0.36 v per ft/sec. The meter was mounted on a stand 2 ft downstream from the cable.

All data were recorded on a four-channel FM instrumentation tape recorded. This allowed simultaneous recording for four of the five instrument outputs, as well as occasional voice comments. Data were recorded until the cable stopped strumming, at which time divers dismantled the apparatus.

EXPERIMENTAL RESULTS

A principal goal of this research was the accurate characterization of the observed strumming motion. This necessarily requires description in terms of Strouhal numbers, average and peak amplitudes, and frequency distribution of the vibration energy. A spectrum analyzer was used in evaluation of the recorded data.

The observed Strouhal numbers were usually in the range of 0.16 to 0.18, which differs from the classical value of 0.21 for rigid cylinders, but agrees with results found by other investigators of vibrating cables. The dominant feature that controlled the nature of observed response in this experiment was the phenomenon known as lock-in. When the predicted Strouhal frequency is far from a natural frequency of the cable, the vortex shedding drives the cable vibration at the Strouhal frequency. As the Strouhal frequency approaches a natural frequency of the cable, the commonly observed synchronization or lock-in of the shedding and natural frequency occurs. If the preferred shedding frequency is very close to the natural frequency, then a condition referred to here as "resonant lock-in" occurs. The response observed in these experiments is described in terms of nonlock-in, nonresonant lock-in, and resonant lock-in behavior. Real-time chart recordings are provided with the following descriptions of each type of response.

Resonant Lock-In

Very regular motion took place when the Strouhal frequency coincided with one of the first four or five natural frequencies of the cable. Fig. 3a shows a strip chart recording of the fish output. The cable displacement is clearly sinusoidal, and the amplitude remains essentially constant. As expected, the spectrum analysis of the record is characterized by a single sharp peak at the frequency of vibration. For the cables tested, this resonance phenomenon occurred when the preferred shedding frequency was within a few percent of one of the first four or five natural frequencies. The observed amplitudes were approximately ± 0.7 cable diameters.

Under resonant conditions the vibration is said to be self-excited. The amplitude would tend to infinity, but equilibrium is reached when the energy lost in dissipation is equal to the energy input to the system from the flow. The dissipation arises from internal friction, radiation, transmission to the supports, and viscous losses in the fluid. Values for the damping were not determined in this experiment.

Nonresonant Lock-In

Lock-in can be found in an additional band outside the narrow frequency range in which resonance occurs. The result in this region is an unsteady motion (Fig. 3b). The basic strumming frequency is the natural frequency, but the amplitude is no longer steady. The amplitude trace shows occasional stoppages of motion and occasional displacement peaks that exceed the regular amplitudes of the resonant motion. The spectrum analysis for this nonresonant locked-in sample shows a strong peak at the natural frequency, but with a broader band width than for the resonant records. The average amplitude is less than that of a regular section, being typically on the order of ± 0.2 diameters.

This distinction between resonant and nonresonant was emphasized at times during the experiment when the tension (and, therefore, the natural frequency) was constant and the flow velocity varied slightly. In one clear case, as the current increased by 5 percent and later decreased, the fish trace shows a simultaneous transition from regular to unsteady and back to regular. The change in natural frequency due to change in drag force was negligible.

Nonlock-In Behavior

Fig. 3c shows an example of nonlock-in motion. The amplitude fluctuations are much more severe than in the unsteady case. This is the expected record when the vibration is at the Strouhal frequency, away from the natural frequencies of the cable. Spectrum analysis reveals a peak at the shedding frequency, but with a broader bandwidth than the other two cases.

The additional frequency components may be introduced by interactions with the nearest natural frequencies or by the small nonuniformities in flow speed along the test length. These variations, within 3 percent of the mean, are probably responsible for the fact that strong lock-in was not observed at the higher frequencies. A small percentage change in current produces a larger absolute change in preferred Strouhal frequency when the current is high than when it is low.

Therefore, at high velocities current inhomogeneities would have a stronger tendency to excite a number of frequencies in the cable. The cable might well be responding with more than one mode at any given time, preventing strong lock-in from occurring.

Beating Phenomena

The wake capture or lock-in phenomena occurred most readily when the shedding frequency was near the first or second natural frequency of the cable. When the Strouhal frequency was between these first two modes, the cable would often vibrate with a strong regular beat. The two frequency components could be either the two adjacent natural frequencies, or one natural frequency and the preferred Strouhal frequency. Small current variations along the cable could account for excitation at both frequencies. Occasionally beating occurred at higher frequencies. Fig. 4 is an example in which the frequency component at 13.1 Hz corresponds to the estimated eighth natural frequency of the cable.

Tension Variation

When cable tension was varied over a short period of time, the effects were the same as holding tension constant and allowing current speed to change. Changing tension alters the relative spacing of the Strouhal and natural frequencies and, therefore, changes the vibration response. Fig. 7 shows the effect of a change in tension.

Spanwise Correlation

Holding one accelerometer fixed and traversing the other revealed the relative phases of motion at different points along the cable. For a taut cable vibrating in the mode shape corresponding to a natural frequency, there is a 180° phase shift at each nodal point. When the vibration was locked in to a natural frequency, the record revealed the expected pattern of phase shifts along the cable length. This behavior was evident especially at the lower modes, but it was also observed as high as the sixth or seventh mode. Under non-locked-in conditions, no regular phase pattern could be found.

At no time did the instruments indicate that any one part of the cable was behaving independently of the rest. If lock-in occurred, the entire cable locked in. Spanwise similarity of vibration seemed to be the rule. At times an accelerometer near one of the support posts would show a strong component of the second harmonic of the strumming frequency. This seems to be an end effect, as it was verified that the amplitude of this second harmonic decreased rapidly as the accelerometer was moved away from the post. Both the drag forces and the tensile forces have fluctuations at twice the cable vibration frequency; this could be responsible for the observations.

Antistrumming Devices

A special experiment was performed in order to test the effectiveness of an antistrumming fairing. The fairing was removed from one-half of a 150-ft section of the braided Kevlar. The cable was then arranged (Fig. 6) so that both halves could be deployed simultaneously, one directly above the other, with the same tension on each. In this way both sections were exposed to identical flow conditions. The fish was placed on the lower (unfaired) section, and an accelerometer was mounted directly above it on the faired section. A sample of the results can be seen in Fig. 5. The fairing had the effect of reducing the strumming frequency, but did not significantly reduce the amplitude.

SUMMARY

On the whole, the cables in this intermediate-sized experiment appeared to behave very much like the shorter sections tested in laboratories. Lock-in occurs when the Strouhal frequency approaches a cable natural frequency. In a smaller band within the range in which lock-in occurs, the vibrations are resonant, or self-excited, their amplitude limited by the energy losses in the system. Resonant lock-in produces greater mean amplitudes than the non-resonant and nonlocked-in conditions, but the largest individual displacement peaks are found in the latter cases.

The experimental arrangement proved to be an effective and convenient means of testing moderate lengths of cable. The test site provided the uniform flow required to permit a controlled experiment. Especially important is the capability to test two different cables simultaneously. The fish developed for this experiment is a useful means of obtaining a direct output of the cable displacement.

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TABLE I - SUMMARY OF CABLE STRUMMING DATA

	Sampson Blue Streak	Wire Rope	Phyllistran	Anti-Strumming Kevlar w/w.o. Fairing*
Measured diameter (inches) under tension	.39	.275	.485	.154
Linear density in air (lb/ft)	.044	.073	.076	.011/.010
Construction	12-strand single braid, polyester and polypropylene	3 x 9 torque balanced galvanized plow steel	7 x 7 "Kevlar" with polyurethane jacket	Braided polyurethane impregnated Kevlar, with 3 twisted conductors down center
Breaking strength (lbs)	5000	4000	17000	2000
Current range (ft/sec)	.26-2.1	.2-2.4	.25-2.2	1.6-2.1
Reynolds no. range	660-5200	360-4200	800-6850	1500-2100
Frequency range (Hz)	1.3-11.3	2.2-18.3	1.5-12.1	14.3-21.3/19.0-27.8
Strouhal no. range	.16-.18	.16-.18	.20-.22	.12-.13†/.17
Tension range (lbs)	70-230	60-580	110-450	65-80
Typical amplitude (diam)	.4-.7	.4-.7	.3-.5	.5†/.5-.7

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*Fairing: 1/16" synthetic fuzz woven helically into Kevlar braid.

†Based on unfaired diameter.

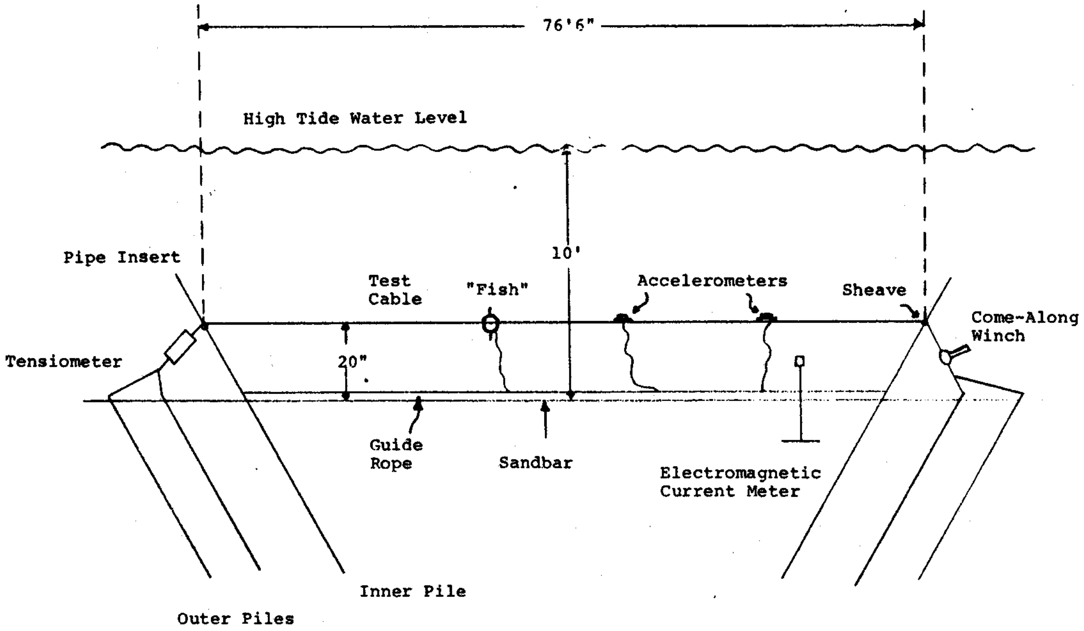
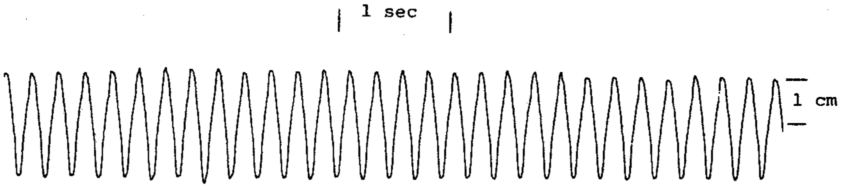
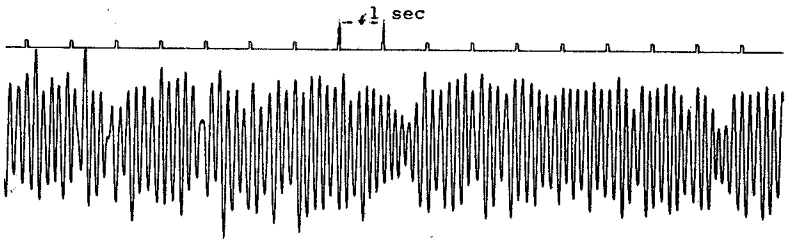


Fig. I - Test cable support arrangement.

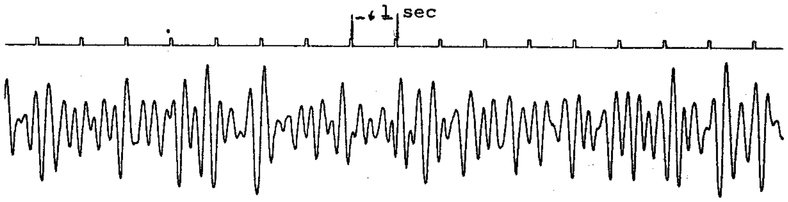
Fig. 2 - The "fish" in position behind the cable.



a) Resonant lock-in. Wire rope. Tension: 360 lbs, current: .6 ft/sec, 4.2 Hz. Displacement .152"/cm on trace. Second mode.



b) Non-resonant lock-in. Blue Streak. 175 lbs, 1.2 ft/sec, 5.75 Hz, .152 "/cm on trace. Fourth mode.



c) Non-lock-in. Blue Streak. 170 lbs, .8 ft/sec, 3.9 Hz, .152"/cm on trace. Between second and third modes.

Fig. 3 - Representative examples of the "fish" record.

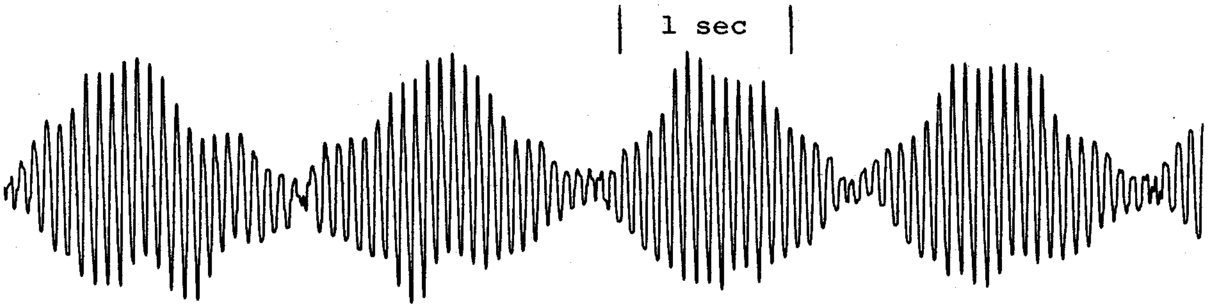


Fig. 4 - Pronounced beating. Wire rope at 180 lbs tension. Current: 1.9 ft/sec, displacement: .152"/cm on trace. Component frequencies: 13.1 and 13.7 Hz.

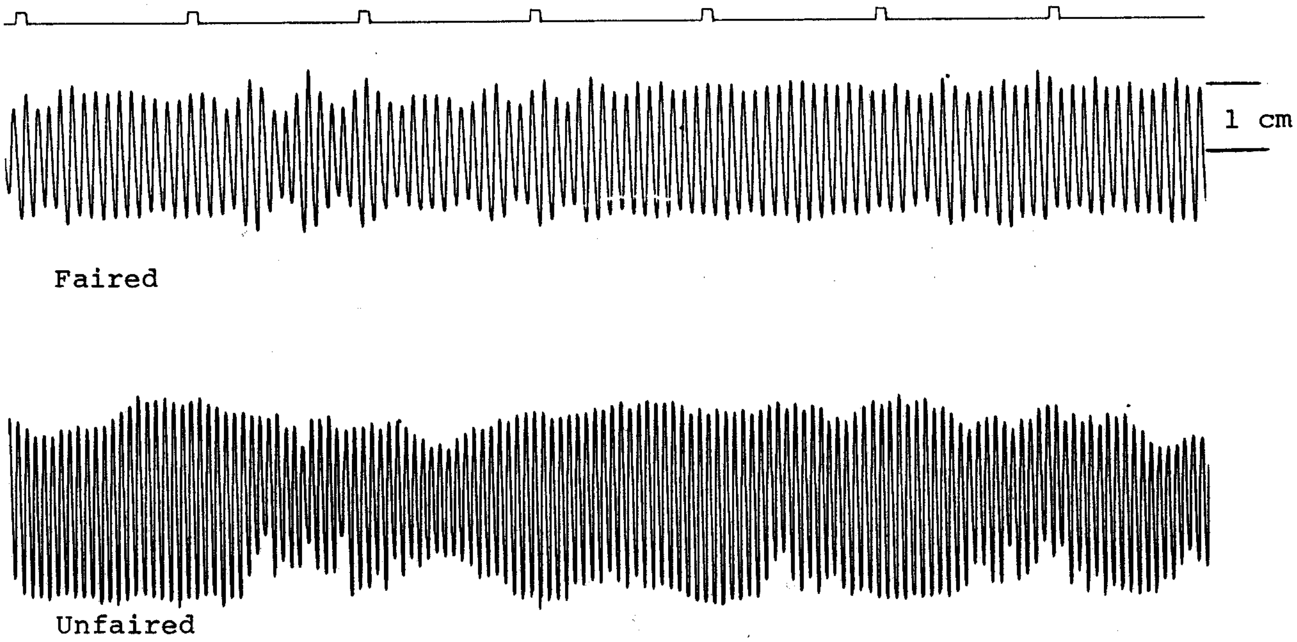


Fig. 5 - Test of anti-strumming fairing. Tension: 65 lbs, current: 1.5 ft/sec. Faired section (top): 14.3 Hz, displacement .06"/cm. Unfaired section: 18.9 Hz, displacement .076"/cm.

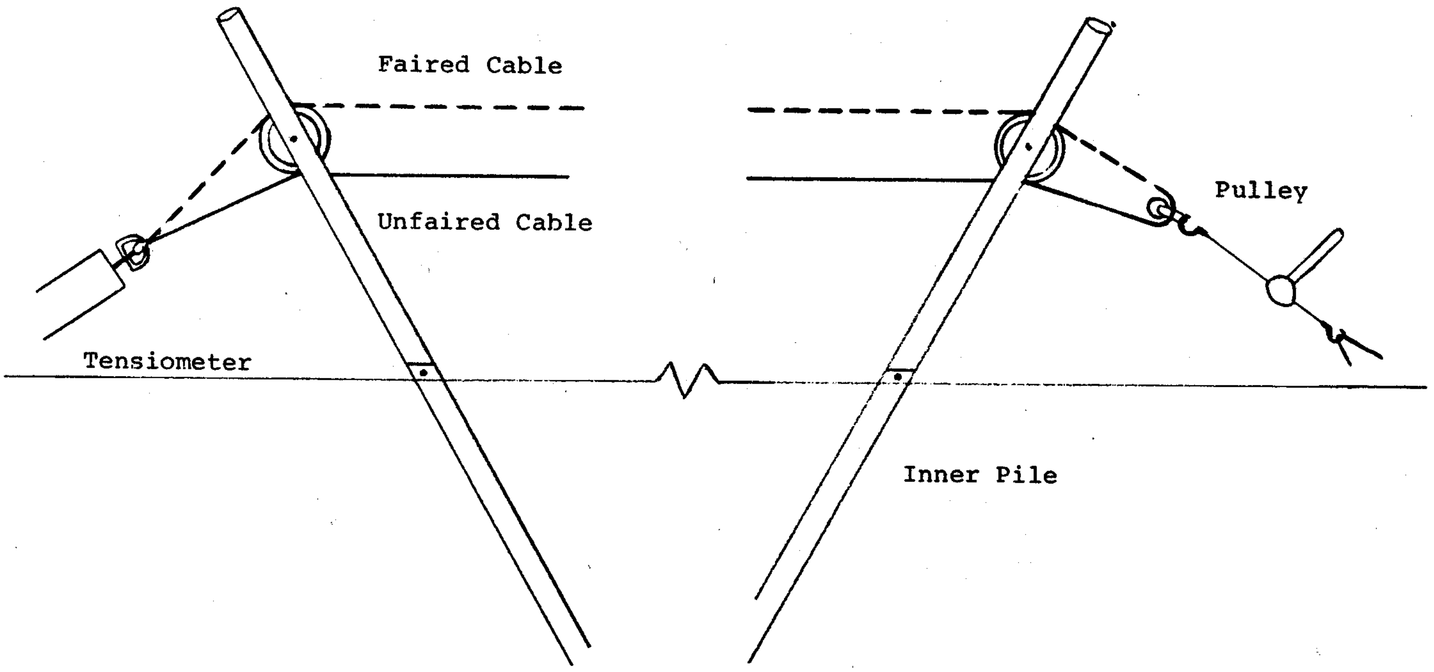


Fig. 6 - Cable arrangement for test of anti-strumming fairing.

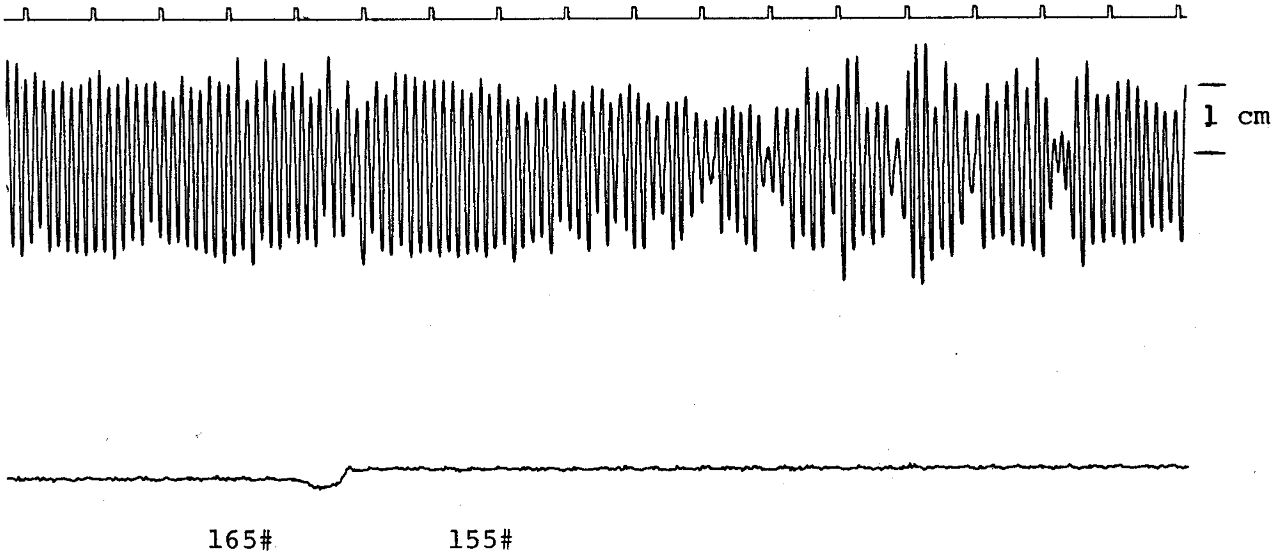


Fig. 7 - Effect of tension variation. Tension decreases from 165 to 155 lbs. Current 1.3 ft/sec, 7.25 Hz. Displacement .152"/cm on trace.