Spurious Signals from Cable-Suspended Sonar Systems

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Spurious sonar signals from ASW systems in the dynamic ocean environment, particularly those resulting from the hydromechanical flow-excitation phenomenon, plague motion-sensitive equipment. Standing wave cable vibrations (cable strumming) and tone effects are characteristics of flexible cables in ocean currents. The magnitude of the water drag on a cable has been found to depend on cable strumming, increasing drag coefficients by as much as 35%. Results of recent studies show why the energy exchange to cylindrical shapes (i.e., flexible cables, hydrophones, and other components) is enhanced and limited by the transverse flow-excited vibrations. Engineering criteria based on these results provide effective designs to negate the causes of spurious signals from sonar systems.

Nomenclature

d = diameter, ft
f_o = oscillation frequency, Hz
f_s = vortex shedding (Strouhal) frequency, Hz
l = standing wavelength, ft
M_c = cable mass per unit length, slugs/ft^2
S_t = Strouhal number
T = cable tension, lb
U = water-flow velocity, fps

Introduction

THE term "spurious signal" refers to any audio signal from sonar systems which does not originate from an ASW target. The sources of such signals may be broadly categorized into ambient acoustical sources and sonobuoy-induced (or hydromechanical) sources. Examples of ambient sources are sea animals, shipping, rain, and wind. The sonobuoy-induced sources are hydromechanical in that they are the result of interaction between the moored or drifting sonobuoy system and the sea environment. Sounds from these sources are frequently assumed to come from sea animals. The majority of species have principal frequencies between 75 and 300 Hz, which is within the range of ASW target signals.

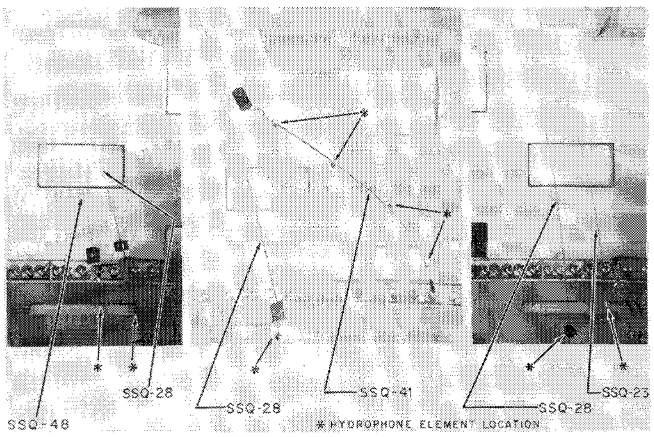

Fig. 1 Typical hydrophone suspensions.

Underwater acoustic systems are inherently prone to the adverse effects of both wave forces and underwater flowfields. The hostile ocean environment induces motion of the associated hydrophone and the supporting cable, and a variety of spurious hydrophone signals result.[1–3] Because of a desire for improved signal recognition, these hydromechanical effects are of interest.

A few of the varieties of suspended single element and line hydrophones are shown in a $\frac{3}{4}$-knot flowfield (Fig. 1). The hydrophones are suspended from both noncompliant and compliant (elastic) cables, with and without cable fairings and line mass. These design variations are intended to attenuate wave-induced vertical cable motion transmitted to the hydrophones and flow-induced cable vibration, termed cable strumming. Typical of the spurious signals from a hydromechanical source are the strum bands illustrated in the lofargram of Fig. 2. The lofargram is a time-based signal frequency spectrum. The signals are data-processed by lofar (low-frequency analyzing and recording) apparatus and the frequency components are plotted against a time base. The intermittent frequency bands representing multiple harmonics can be seen. Degradation of a target signal during these periods frequently occurs. The bands caused by a common hydromechanical cable-strumming effect result when there is a water-flow relative to a cable suspending a hydrophone.

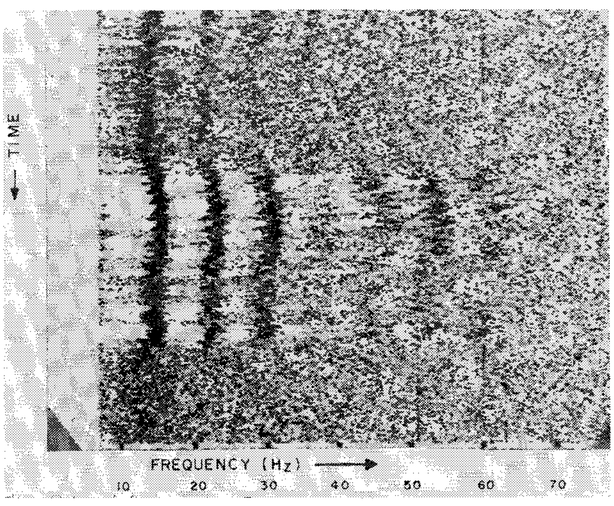

Fig. 2 Lofargram data display.

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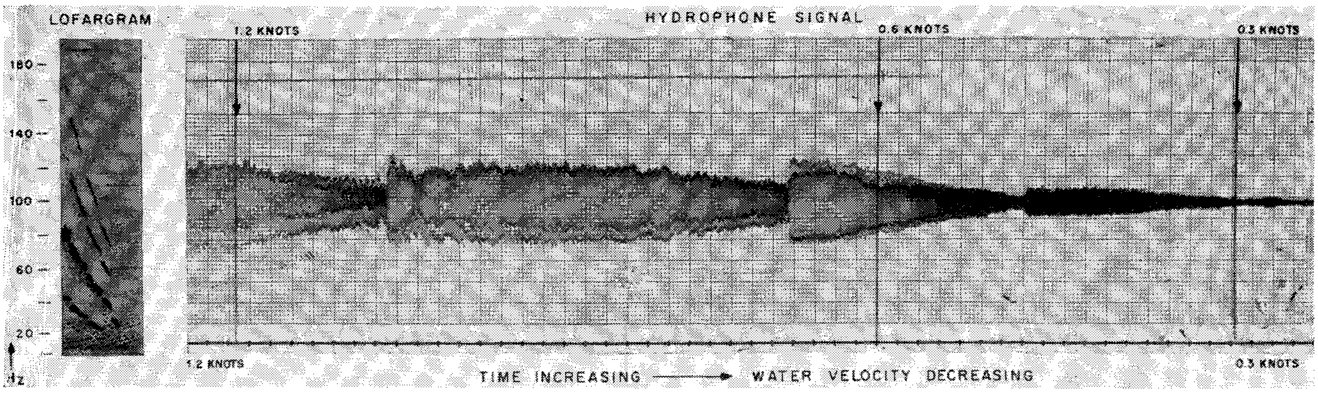

Fig. 3 Typical hydrophone signal indicating cable vibration modes; 1-sec time pulses indicated.

Relative Water Flow

Associated with these ASW systems are both the moored and drifting types of hydrophone suspensions. In the moored system the hydrophone is suspended on a taut or slack cable attached to a subsurface or surface float. The motion of the moored hydrophone suspension is influenced to some extent by the motion of the surface waves, depending on the depth of the float and the design of the mooring. The moored system is subjected to the water-flow forces related to the in situ absolute water-velocity profile.

In contrast to the moored system, the drifting sonobuoy system experiences the water-flow forces associated with the water-velocity profile relative to the drifting system. The magnitude of this relative profile depends not only on the absolute velocity profile but also on the fluid drag characteristics of the system.

The water velocity relative to the suspension cable is significant, since it is a necessary environment for cable strumming. Velocity profiles relative to the moored system are known to range between $\frac{1}{4}$ and 3 knots within the worldwide ocean areas exclusive of the few localized severe currents (i.e., Gulf Stream, Kuroshio, and Agulhas currents). For the drifting systems, a velocity gradient, or differential flow, is required if a flowfield relative to the cable is to result. It is apparent that the deeper the hydrophone is suspended in a drifting system the more chance there is of a differential flow, particularly if the hydrophone is below the thermocline, wherein the velocity gradient decreases markedly. For drifting hydrophones suspended at a depth of 100 ft, maximum differential water flows of 1–2 knots are thought to be realistic. Even in quiescent water the surface wind and wave transport may force the system in such a direction as to cause a differential flow relative to the cable. These capricious surface effects can be assumed to cause a 1-knot surface flow.

The foregoing considerations serve to illustrate that one must have knowledge of the water-velocity profile, the cable suspension design, and the manifold surface conditions before predicting a water-flow environment relative to the cable.

Signal Frequency Ranges

The spurious hydrophone signals can be broken down into three characteristic frequency ranges: 1) 0.1–1.0 Hz (static-pressure head variations), 2) 1.0–5.0 Hz (dynamic-pressure head variations), and 3) 5.0–200 Hz (cable strumming).

The first range (0.1–1.0 Hz) of signals is produced by variations in the static-pressure head caused by surface effects—the wave-induced motions. The second range (1.0–5.0 Hz) is produced by dynamic head changes on the hydrophone caused by the periodic forced motions of associated sonobuoy elements that are not flow-stabilized. Although the sound electronics is responsive to frequencies higher than those in these ranges, the signal level generated within the two ranges is often much greater than the electronics is capable of accommodating. Some of the effects of this high signal level are electronic circuit saturation and/or high-frequency transients.[3] The third range of spurious signals (5.0–200 Hz) is the result of periodic forced cable vibrations, or cable strumming, that excite the acceleration-sensitive hydrophone.

Greater emphasis is placed on the dynamic pressure head and cable strumming sources because they are the result of flow excitation. These adverse effects are more common, since they are induced by both subsurface water flows and surface wave forces.

Flow Excitation

Flexible Cables

It is well known that water flow relative to an elastic cylinder will cause vibration because of periodic hydrodynamic forces associated with the formation of shedding vortices.[4] This phenomenon (the vibration) can be readily appreciated if one moves an extended finger or tows a string supporting a weight in water. Periodic water forces are apparent on either side of the finger, whereas with the string one feels the resulting vibration. Since the water forces act on the sides of the moving object, the forces produce motion in the plane normal to the water flow. Accordingly, the term "transverse vibration" is commonly associated with these side forces, frequently designated "lift" forces. Periodic drag forces, at twice the lift-force frequency, also act in a direction parallel to the flow. Since their magnitude is of the order of $\frac{1}{10}$ of the side-lift forces, the motion effects associated with periodic drag are not usually apparent.

Consider now a flexible hydrophone suspension cable exposed to a relative water velocity. The large amplitude transverse vibrations occur at a discrete frequency which forces the flexible cable into a discrete number of vibrating sections, or standing waves.[1] The approximate frequency of vibration and the length of the vibrating sections can be estimated using the Strouhal relation and the string equation, respectively.

The Strouhal relation is

$$S_t = f_s d/U \qquad (1)$$

where the dimensionless Strouhal number S_t depends on the Reynolds number and can be obtained from any appropriate reference.[5] (It is approximately 0.2 for 300 < Reynolds number < 100,000.) The Strouhal frequency f_s is the frequency of natural vortex shedding and not of cable vibration. There are subtle differences between these frequencies. The Strouhal frequency is controlled by the fluid and varies linearly with velocity; however, the vibration frequency is uniquely dependent on the ratio of f_s to the natural system frequency.[6] When the elastic cylinder is a flexible cable, there is a natural frequency associated with each harmonic vibration. The vibration frequency exhibits transitional steps between harmonic modes; however, the mean frequency is nearly linear with water velocity.[2]

When the cable streams under the influence of static drag forces, the velocity term U should be taken as the component water velocity in a direction normal to the cable.

Although these factors compromise the use of the Strouhal relation for accurate determination of the vibration frequency, the relation is a good diagnostic means for isolating cable strumming sources (i.e., knowing the water velocity and vibration frequency, the cable diameter can be estimated). The Strouhal relation can be used for design calculations provided it is understood that the Strouhal and oscillating frequencies can differ by as much as 20%.

For Reynolds numbers less than about 50, the vortices do not shed and, therefore, do not generate periodic side forces. This should be considered where small diameters are used with low relative velocities.

The following string equation can be used to estimate the length of the vibrating sections[1] (distance between nodes):

$$l = (T/M_c)^{1/2}/2f_n \tag{2}$$

By combining Eqs. (1) and (2), cable diameters and lengths can be selected to avoid resonant cable vibrations on short cables.

Vibrational characteristics of a flexible cable are readily observed when the signal from a motion-sensitive terminal hydrophone is recorded. A hydrophone supported by a flexible cable experiences acceleration forces similar to those felt by the experimenter towing the string. Hydrophones (particularly the crystal and ceramic types) are generally sensitive to accelerations, and high-level spurious signals result when the cable strums. Figure 3 illustrates a typical signature when the water velocity uniformly decreases from 1.2 to 0.3 knots and the hydrophone is suspended by 3 ft of 0.1-in.-diam cable. Each triangular envelope corresponds to a different harmonic vibration mode. The fundamental is at the low-velocity end and each successive triangle represents the next higher harmonic (5 harmonics are represented). The transitions in signal level define the limits of each harmonic vibration mode. Transitions in frequency occur at these boundary velocities and are illustrated on the lofargram in Fig. 3. The bottom is the hydrophone-signal frequency and the upper three lines represent higher (low-level) harmonics, vibrating in sympathy with the exciting vortex forces. The frequency jump is analogous to a change from one musical note to another on a stringed instrument.

The influence of harmonic modes of vibration is also seen in the measurement of water drag on the cable. The static drag on the cable causes streaming of the cable and the possibility that the hydrophone will not be suspended at its design depth. (A cursory method of computing this is by use of a force balance analog.[7]) This adverse effect is enhanced by cable strumming which may increase the drag by as much as 35%.[8] Increased drag due to strumming varies from one harmonic to another so that the tension to which the cable is subject and the amount by which it streams depends at any point in time upon the mode of cable vibration. Flexible cable drag can be calculated towing a free cable with a standard terminal weight.[9]

The vibration modes for longer cables are inherently more complex because the long cable streams and bends with the water drag forces. This results in a nonuniform velocity component normal to the cable, and according to Eq. (1), the excitation frequency will be nonuniform. This also occurs when shear currents are present—when the velocity profile is nonuniform along the cable length. A hydrophone on a long cable senses the excited vibrations over a broader frequency band that reflects this velocity variation. The interactions between cable vibrations excited at different cable sections result in signal beating and random groups of regular vibrations at the hydrophone station.

Typical sonobuoy hydrophone suspension systems incorporate both short cables ($\frac{1}{2}$–3 ft) and long cables (up to 1500 ft). As illustrated in Fig. 1, short cables are used between line hydrophone elements and associated bodies. Long cables suspend the hydrophones from the surface buoy.

The flexible suspension cable will respond to alternating relative flows, induced by wave actions, by strumming in a series of bursts. The burst sequence is related to the wave periods. Such alternating flows are common and result from the following causes.

1) Surface wave forces on the surface float induce a distorted circular response of the hydrophone and cable.[10] When the hydrophone and cable are at the top and bottom of the cycle, the relative flow will be normal to the supporting cable. The flow direction will alternate by 180° between the top and bottom positions. Periodic cable strumming will result.

2) The water-particle motion associated with surface waves decays with depth and usually results in insignificant flow fields of less than 0.1 knot at 100 ft. At shallower depths, the wave-induced particle motion represents an alternating periodic flow capable of inducing strumming.

3) Internal waves will exist beneath the surface if the sea has certain density stratification characteristics. These waves will cause similar alternating periodic flows, frequently of high magnitude, and they are not easily predictable as a function of depth.

Cylindrical Components

The Strouhal frequency-velocity concept discussed earlier also applies to any cylindrical component which is part of the hydrophone suspension. These include hydrophones, preamplifier housings, and terminal masses. When these unstable bodies are placed in a relative flowfield, they may oscillate transversely at a frequency related to the velocity by the Strouhal number. These frequencies are generally low, of the order of 1–5 Hz, because the body diameters are considerably larger than the cables considered.

The resulting motion is the so-called "fishtailing" or low-frequency sideways motion. This motion causes a periodic variation in pressure on the hydrophone because of the water-loading effects.

The amplitude of the motion depends on the manner in which the component is suspended. The suspension cable may act as a torsion spring and the component will experience resonant vibrations if the Strouhal frequency corresponds to the natural torsional frequency. Occasionally, the component and suspension cable will be equivalent to a pendulum. Resonant pendulous vibrations occur when the Strouhal frequency corresponds to the natural frequency of the pendulum.[10]

Basic Concepts

The mechanism of flow excitation is being studied with the objective of finding ways to negate the periodic excitation and, therefore, the adverse periodic motion effects. Certain significant results have been obtained by observation of the vortex wake of both vibrating and nonvibrating circular cylinders.[11] The wake is conveniently visualized using an electrolysis technique wherein hydrogen bubbles are generated at the surface of the cylinder. The water flow carries the bubbles into the cylinder wake where they effectively define the spanwise vortex lines.

Since the side exciting forces are associated with these vortices, the spanwise phase relationship of the forces can be observed. When the cylinder is towed through water at a velocity that will not excite transverse vibration, the vortex wake appears as a series of vortex lines as shown in Fig. 4. The circular cylinder is in the form of a flexible rod to simulate a flexible cable or an elastically supported rigid cylinder. Notice that the vortex lines are shed generally parallel to the rod but appear as a series of interconnected sinuous loops,

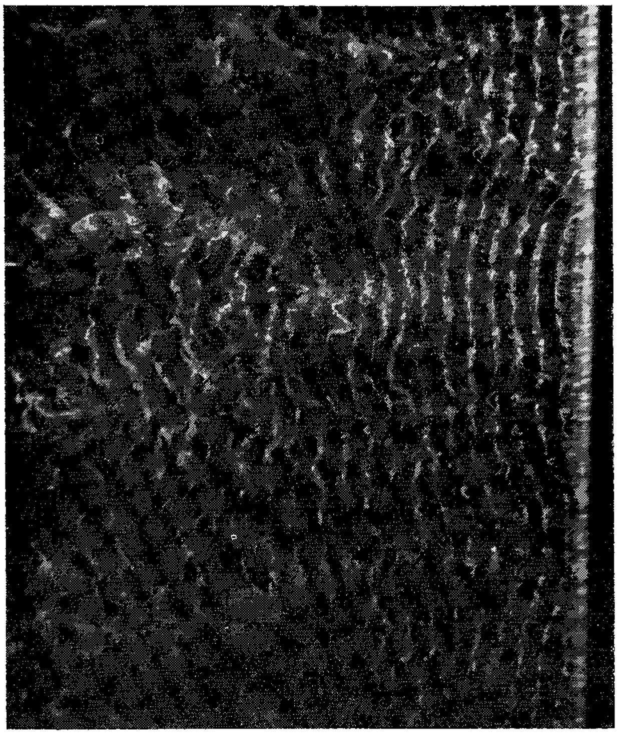

Fig. 4 Natural vortex shedding from a nonvibrating cylindrical 0.05-in.-diam rod towed in water (flow visualization by hydrogen bubbles).

indicating that the phase of shedding is not correlated along the entire span. Phase differences (referenced to a shedding cycle) of up to 120° have been reported.[12] This implies that the side vortex forces are not in phase along the span. Therefore, the magnitude of the total exciting force is less than if the line vortices were correlated. This loop-type shedding is termed nonmotion-dependent vortex shedding because it is a natural form of shedding and does not depend on transverse vibration (motion). Tenable concepts of motion dependence and other fluid-excitation criteria have recently been formulated.[13]

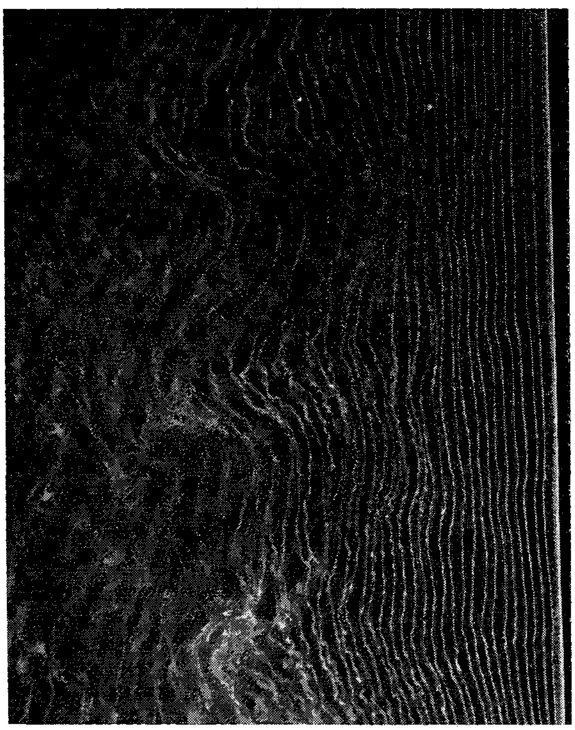

Fig. 5 Forced vortex shedding from a flow-excited 0.05-in.-diam rod vibrating transverse to the direction of tow in water (flow visualization by hydrogen bubbles).

The rod is flow-excited into transverse vibration when the excitation frequency is close to the natural frequency. This transverse motion forces the line vortices to shed at the rod vibration frequency.

The effect is shown in Fig. 5, where the tow velocity is adjusted to excite the rod in its fundamental vibration mode. Each line vortex is shed parallel to the rod, implying that the side exciting forces are completely correlated spanwise. The effective magnitude of the total side force is greater, compared to the loop-type shedding, and more hydro-energy is transferred to the rod. The shedding vortices are termed motion-dependent for this parallel form of shedding.

Wake observations indicate that the nonmotion-dependent (natural) shedding occurs when the amplitude of vibration is low (less than 10% of the diameter). This form of shedding can also occur when the amplitude has reached its maximum value.[6,11,13] The Strouhal frequency equals the vibration frequency for this condition and the fluid vortex force is maximized.[14] If now the water velocity increases, the Strouhal frequency will exceed the vibration frequency and the shedding reverts to a nonmotion-dependent form. Since the vortex forces are no longer correlated for this form of shedding, the transverse amplitude decays significantly.[15]

This fluid mechanism appears to limit the maximum transverse amplitude and thus the hydro-energy transferred to the rod. If nonmotion-dependent vortex shedding can be induced when the flow-excitation frequency is in the vicinity of the natural vibration frequency, the transverse motion can be negated or reduced significantly. This concept is under active study.

Design Engineering

The design of a motion-sensitive underwater platform can now be logically approached, considering the concepts that have been discussed. The physical model considered is a typical sonobuoy suspension consisting of the components illustrated in Fig. 6. The following comments can be applied to any motion-sensitive platform that is cable suspended in the ocean. It is important to appreciate the sources of flow-excited motion; then the isolation techniques can be applied effectively.

The long cable (Fig. 6) significantly influences the depth of the suspension because of the water drag forces. It is also a source of cable strumming that must be isolated from

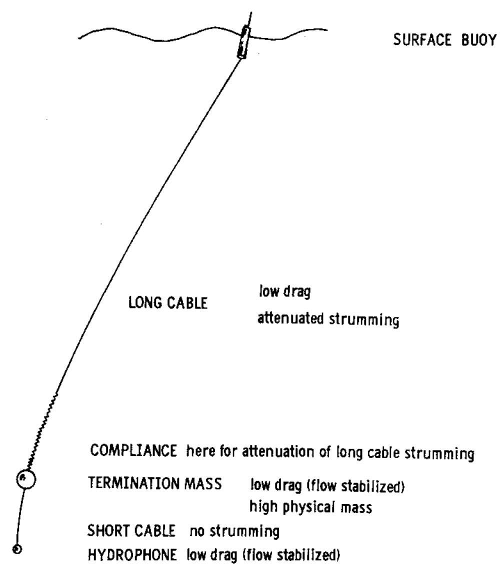

Fig. 6 Design concepts for negating spurious hydrophone signals.

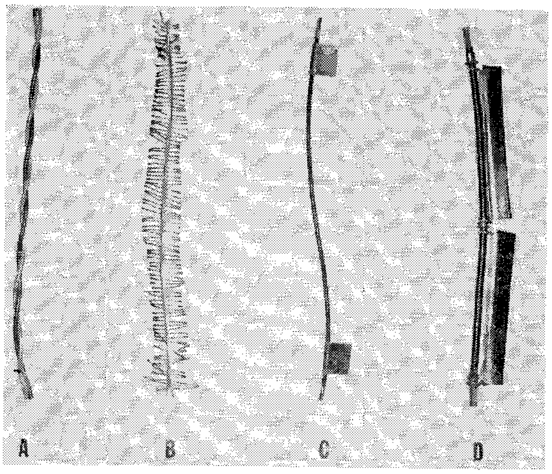

Fig. 7 Cable designs with special omnidirectional drag and strumming characteristics; A, twisted pair; B, haired streamers; C, antinode splitter; D, weathervane fairing.

the hydrophone. For these reasons, the cable should have low drag and attenuated strumming characteristics. The "twisted pair" of cables illustrated in Fig. 7 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.[8] 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.[16]

When a compliant cable section is employed for attenuation of wave motion it should separate the long-cable strumming source from the termination mass. The compliant cable will attenuate the strumming forces and provide partial isolation from the hydrophone.

Both the termination mass and the hydrophone should have streamlined envelopes or at least have spherical ones. As long as they are not cylinders, there will be no periodic motion from flow excitation. The termination mass usually features a large virtual mass (equivalent water mass) for the purpose of wave-motion attenuation. The virtual mass is not totally effective in attenuating strumming forces because the motion amplitude may be only a few thousandths of an inch. Bending of the load members by this amount makes the virtual mass ineffective. For effective attenuation of the accelerating forces, a physical mass, as large as can be accommodated, should be employed.

The short cable must be designed to eliminate strumming even at the expense of increased drag. The "haired-streamers" design illustrated in Fig. 7 is stable when the hairs are attached to the downstream edge; however, the drag is increased about 20%.[8] 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 short cable should also be compliant such that the combination of cable (spring) and hydrophone (mass) have a natural (spring-mass) frequency at least an order of magnitude lower than the frequency of the predicted strumming forces from the long cable.

The "antinode splitter" cable design of Fig. 7 is partially effective in reducing strumming when the splitter tabs are placed at the predicted cable antinodes.[8] An effective tab geometry is 10 diam with the stream and 20 diam along the cable. The "weathervane fairing" (Fig. 7) consists of streamline omnidirectional tabs. This design is flow-stabilized and reduces the drag almost 50%; however, fabrication costs would be high.[8]

The information presented herein should provide the design engineer with a cursory knowledge of flow excitation and what can be done about it. The indicated references offer a comprehensive coverage of the applied research from which many of these results were obtained. They should prove useful for supplemental information, and collectively they provide an up-to-date bibliography on this specialized subject.

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