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The Effectiveness of Helical Strakes in the Suppression of High-Mode-Number VIV

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Abstract

Triple helical strakes can play an important role in the suppression of VIV on offshore platforms. This paper will present results of two field experiments, one conducted at Lake Seneca in upstate New York and the second in the Gulf Stream near Miami, Florida. Three different distributions of triple helical strakes were tested. These experiments were designed to explore the effects of VIV on both bare pipes and pipes with strakes at mode numbers greater than the tenth mode in uniform and sheared currents. At Lake Seneca, bare pipe and full strake coverage pipes were tested in uniform currents. In the Gulf Stream two different configurations of strakes were tested and compared to the VIV response of a bare cylinder. The two configurations are referred to as the 40% coverage case and the 70% staggered coverage configuration. The results of these tests showed a reduction in the amplitude of the vibration and also the frequency content of the vibrations. In particular, a large third harmonic component, which contributes significantly to the fatigue damage rate, was suppressed by the configurations with strakes. Together these reductions will greatly increase the fatigue life of the pipe.

Introduction

The tests at Lake Seneca were conducted in the summer of 2004 and focused on the measurement of VIV in uniform flow at high mode number for a bare pipe and for the same pipe with complete strake coverage. In comparison, the Gulf Stream tests were conducted in October and November of 2004 and focused on bare pipe and partial strake coverage with sheared flow. Both tests are part of a larger VIV testing program developed by DEEPSTAR (A joint industry technology development project).

As oil exploration and drilling moves into deeper water, understanding the dynamics of long pipes, vibrating at high mode numbers in sheared currents, becomes important. Additionally, understanding how strakes affect the dynamics of bare pipe is also important. The main objectives of the Gulf Stream Test were:

- To gather vortex-induced vibration response data using a densely instrumented circular pipe at high mode number,
- To measure mean drag coefficients (C_D) at high mode numbers and improve drag coefficient prediction formulas,
- To test the efficacy of helical strakes at high mode numbers,
- To obtain statistics on the distribution of single-mode vs. multi-mode response to VIV,
- To determine the relative contribution to damage rate, arising from in-line and cross-flow VIV,
- To improve knowledge of damping factors on risers equipped with helical strakes.

Gulf Stream Test Description

The Gulf Stream tests were conducted on the Research Vessel F. G. Walton Smith, operated by the University of Miami. The composite pipe was 485.3 feet long and 1.4 inches in diameter. The pipe was instrumented with fiber optic strain gauges to monitor the vibration.

The pipe was spooled on a drum that was mounted on the aft portion of the boat. The pipe was un-spooled and lowered into the water using a hydraulic motor. At the bottom end was a railroad wheel assembly which included a current meter, a center spool and U-joint. The assembly weighed 836 lbs in air and approximately 725 lbs in water, and was attached to the bottom of the pipe to provide tension. The weight in water of the pipe was 0.12 lb/ft. With additional drag forces on the pipe the typical total top end tension was 820 lb. The pipe was attached to the stern of the boat on a perch. About six feet of pipe were above the waterline. A variety of current profiles with significant variation in speed and direction were achieved by steering the vessel at numerous headings, while in the Gulf Stream.

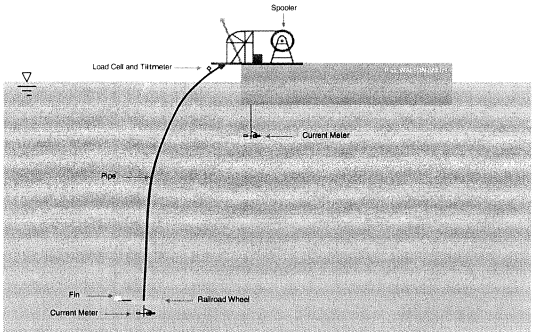

Figure 1 – Experiment Set-up for the Gulf Stream Test

Eight optical fibers were embedded under the outer layer of the pipe during manufacture. Each fiber contained 35 strain gauges, spaced fourteen feet apart. Two fibers were located in each of the four quadrants of the pipe, as see in Figure 2.

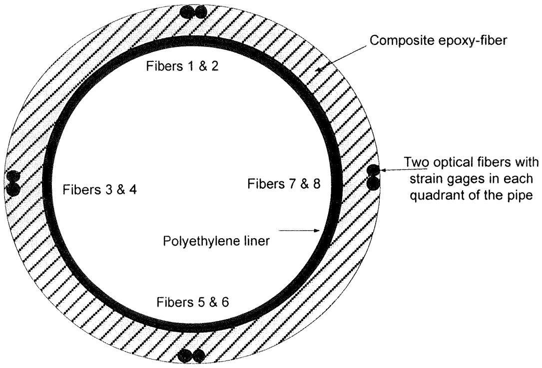

Figure 2 - Cross-Section of the Pipe from the Gulf Stream Test

The gauges in one fiber of a pair were not placed at the same axial position as the gauges in the adjacent fiber. Instead they were offset axially from one another by seven feet, as seen in Figure 3. When both fibers are functioning a spatial resolution of seven feet was achieved. By merging the data from both fibers, an effective resolution was achieved with seventy total strain gauges per quadrant.

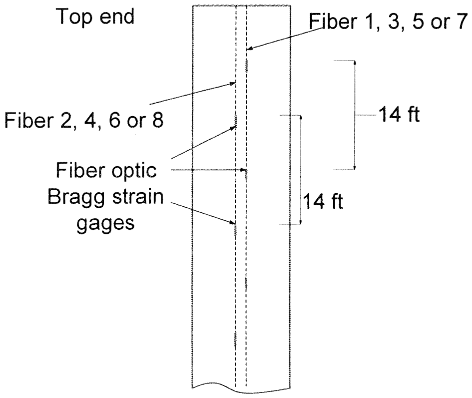

Figure 3 - Side View of the Pipe from the Gulf Stream Test

During the experiments the exact orientation of the four quadrants was not known. This is due in part to a residual twist over the total length of the pipe of approximately 60 degrees, which was introduced in the fabrication process. Although there was a fin on the wheel, which was intended to orient the wheel in the current, the exact current direction at the wheel is not known, because the depth of the wheel varies with drag force. It is known that within the same quadrant, the orientation of the optical fibers varies slowly. The conclusions reached in this paper do not depend on knowing the exact orientation of the strain gauges with respect to the boat. This is not a significant limitation in understanding the efficacy of strakes. It will be shown that there is very little difference in RMS amplitude and frequency content between gauges located in different quadrants

The pipe was made by Hydril and consisted of an epoxy, carbon fiber matrix with an HDPE liner. The pipe properties are found in Table 1.

Table 1 –Gulf Stream Pipe Properties

Inner Diameter	1.05 in. (0.0267 m)
Outer Diameter	1.40 in.(0.0356 m)
Optical Fiber Diameter	1.30 in.(0.033 m)
EI	1.7e5 lb.in^2 (488 Nm^2)
Modulus of Elasticity (E)	2.30e6 lb./in^2 (1.586e10 N/m^2)
EA	8.5e5 lb. (3.78e6 N)
Weight in Seawater	0.12 lb./ft. (flooded in Seawater) (1.75 N/m)
Weight in air, w/trapped water	0.83 lb./ft. (12.11 N/m)
Density	0.053 lb/in^3 (1.47 g./cc).
Material	Carbon fiber --epoxy
Length	485.3 ft (147.3 m) (U-joint to U-joint)
Roughness (k/D)	0.002

An Acoustic Doppler Current profiler (ADCP) was used to record the current along the length of the pipe. An ADCP uses acoustic sound waves to measure current speed and direction. The ADCP sends out an acoustic ping and waits for the return sound. Based on the time the ping takes to return and the Doppler shift in frequency, the ADCP obtains and estimate of the current speed as a function of depth.

The R/V F. G. Walton Smith has high and low frequency ADCPs. The broadband (600 kHz) ADCP is used to obtain a greater resolution and accuracy at the shallow depths, whereas the narrowband (150 kHz) ADCP is used for deeper depths. During the Gulf Stream testing both ADCPs were used to gather data.

Additional instrumentation included a tilt meter to measure the inclination of the top of the pipe, a load cell to measure the tension at the top of the pipe, and two mechanical current meters to measure current speed at the top and the bottom of the pipe.

Lake Seneca Experiment

The Lake Seneca test used a set-up similar to the Gulf Stream test, as shown in Figure 1. The 401 foot long pipe at Lake Seneca was instrumented with 24 tri-axial accelerometers that were approximately evenly spaced down the pipe and one tri-axial accelerometer located on the railroad wheel. A two axis tilt meter and a load cell were deployed at the top end of the pipe, and two mechanical current meters were located at the top and bottom of the pipe. The pipe interior contained the accelerometers and the communications wire. The void space was filled with a flexible epoxy.

At Lake Seneca, the current profiles seen were essentially uniform, with the current over the pipe being equal to the speed of the boat. This response data provides a uniform flow baseline for comparison to the Gulf Steam data.

For further details of the experimental set-up, refer to Reference [1], [Vandiver et al 2004].

Table 2 - Lake Seneca Pipe Properties

Outer Diameter	1.310 in.(0.0333m)
Inner Diameter	0.980 in (0.0249m)
Lengths tested	201 & 401 feet(61.26 & 122.23m)
Effective tension	805 lbs submerged bottom weight (3581N)
Modulus of Elasticity (E)	1805.0 ksi (1.2445e10 N/m^2)
Moment of Inertia (I)	3.994e-06 ft^4 (3.447e-8 m^4)
EI	149489.3 lb.in^2(428.979 Nm^2)
Specific gravity	1.35
Weight in air	0.79 lb/ft(11.53 N/m),(1.176 kg/m)

Strake Properties

The strakes, used for both the Lake Seneca and the Gulf Stream experiments, were a triple helix design made of polyethylene, with a pitch of 17.5 times the diameter of the pipe. This represents a typical design for strakes in the industry. The properties of the strakes are shown in Table 3. The strakes had a slit down the side that allowed them to be snapped over the outside of the pipe, and secured to the pipe using tie wraps. The strakes were manufactured by AIMS International.

Table 3 - Strake Properties

Material	Polyethylene
Length	26.075 in. (0.66 m)
Shell OD	1.49 in.(0.038 m), includes the strake height
Shell ID	1.32 in. (0.0335 m)
Strake Height	0.375 in. (0.009 m) (about 25% of shell diameter)
Wall thickness	0.09 in.(0.0022 m)
Pitch	17.5 times the Diameter
Weight/length in air	0.11 lb/ft ±10% (1.6 N/m ±10%)

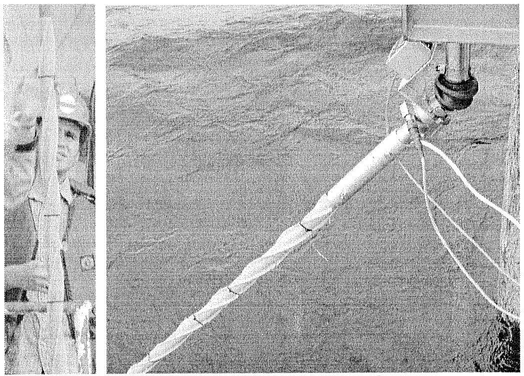

Figure 4 - Strakes Attached to the Pipe at Lake Seneca

For the Lake Seneca Test, two different configurations were examined: bare pipe and 100% strake coverage. For the Gulf Stream test, three different configurations of the pipe were tested: bare, 40% strake coverage at the bottom of the pipe, and 70% strake coverage, which was staggered in 5 approximately equally distributed sections. For the 70% staggered case, the sections covered in strakes are listed in Table 4.

Table 4 - 70% Staggered Strake Locations

Start (ft from the top U-joint)	Stop (ft from the top U-joint)
40.9	103.9
135.5	198.5
230.1	293.1
324.7	387.7
416.3	482.3

Damping Factors for Strakes

On the second day of testing in the Gulf Stream, 40% strake coverage was applied to the bottom portion of the pipe. The bottom one hundred ninety four feet of the pipe was covered in strakes. The vibration was driven entirely by vortex shedding from the bare region of the pipe. The vibration waves generated in this region propagated into the straked region where the waves attenuated rapidly, as can be seen in Figure 5. The magnitude of the observed RMS single channel strain was as high as 200 micro-strain($\mu\varepsilon$) in the bare region and was reduced to less than 25 $\mu\varepsilon$ as the waves traveled through the strake region to the bottom end of the pipe.

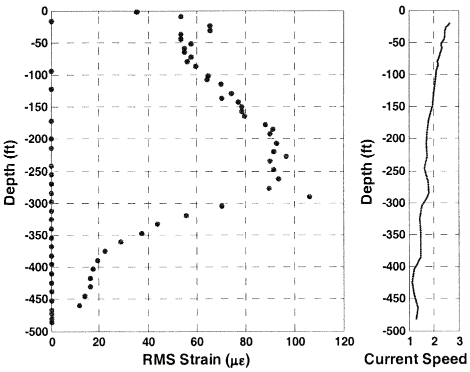

Figure 5 - Measured Single Fiber RMS Strain for 40% Strake Coverage; Shown with the Corresponding Current Profile

An apparent problem created by the partial strake coverage is a stress concentration at the interface between the bare and straked regions. One hypothesis is that for the traveling waves generated in the bare region the change in mass per unit length at the beginning of the straked region caused wave reflections and a local stress concentration.

Upon entering the straked region, Figure 5 shows that the waves attenuated exponentially as modeled in Equation 1.1.

$$y_2 = A\, e^{-\zeta k_2 \Delta x} \qquad (1.1)$$

Equation (1.1) describes the amplitude of propagating waves with exponential decay due to damping, where ζ is the damping ratio, k_2 is the wave number in the straked region, and Δx is the distance between two points. By using a logarithmic fit, the rate of decay for the data shown in Figure 5 is found to be given by the following equation:

$$\zeta k_2 = 0.0114 \, {}^{1}\!/_{ft} \tag{1.2}$$

$$k_2 = \frac{\omega}{c_2} = \frac{2\pi f}{c_2} \tag{1.3}$$

$$\zeta = \frac{0.0114 c_2}{2\pi f} = \frac{0.0018 c_2}{f} = \frac{0.185}{f(Hz)} \tag{1.4}$$

$$\text{for } c_2 = 102 ft/s$$

From this Equation (1.4) the frequency dependant damping ratio, ζ, is plotted in Figure 6, using the measured propagation speed of 102 ft/s in the straked region.

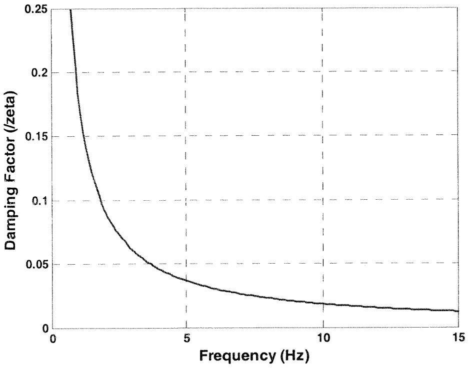

Figure 6 – Estimated Damping Ratio for the Region with Strakes

Analytical Model of the Pipe with Partial Strake Coverage

For the 40% coverage case, the measured response revealed that there was little excitation in the straked region, and furthermore, the presence of the strakes introduced substantial damping of vibration produce on bare regions of the pipe. A simple mathematical model has been formulated to predict this behavior. The model assumes that the pipe behaves dynamically as a taut string: i.e. the tension in the pipe is more important than bending stiffness in determining the transverse wave propagation properties of the pipe. The boundary conditions are assumed to be pinned-pinned.

The pipe is assumed to be made up of two parts, a lightly damped part which represents the bare portion of the pipe and a strongly damped region representing the strakes. The pipe model is excited by a harmonic point force located 180.45 feet from the top end. This point was chosen so as to be inside the likely principal power-in region for actual test shown in Figure 5. Although actual VIV excitation would be distributed over the power-in region, this simple model is able to give us a quick qualitative understanding of the typical expected response and the effect of the presence of the straked region on overall response.

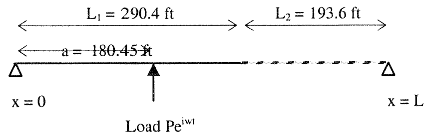

Figure 7 - Schematic of a Numerical Simulation with 40% Strake Coverage.

Figure 7 schematically shows the arrangement considered. It is assumed that the tension is sufficiently large that the bending stiffness of the pipe may be ignored. This is equivalent to saying that the wave propagation speed is a function of the tension, T, and not EI. The equation of motion for the lightly damped portion with a point force is:

$$m_1 \frac{\partial^2 y_1}{\partial t^2} - T \frac{\partial^2 y_1}{\partial x^2} + r_1 \frac{\partial y_1}{\partial t} = \delta(x-a) P e^{i\omega t} \tag{2.1}$$

$$\text{where } c_1 = \sqrt{\frac{T}{m_1}}, \text{ the speed of wave propagation}$$

and that for the straked portion with higher damping

$$m_2 \frac{\partial^2 y_2}{\partial t^2} - T \frac{\partial^2 y_2}{\partial x^2} + r_2 \frac{\partial y_2}{\partial t} = 0 \tag{2.2}$$

$$\text{where } c_2 = \sqrt{\frac{T}{m_2}}, \text{ the speed of wave propagation}$$

m_1 and m_2 are mass per unit length, T is the tension in pipe and r_1 and r_2 are the damping force per unit length per unit velocity in the bare and straked regions respectively.

The required matching conditions at x = L_1, the point at which the straked region begins, are

Deleted: the location of the point force

$$y_1 = y_2 \tag{2.3}$$

$$\frac{\partial y_1}{\partial x} = \frac{\partial y_2}{\partial x} \tag{2.4}$$

The solution for y_1 is obtained by considering the solution to be made up of two parts:

$$y_1 = y_{1L} \quad \text{for } 0 < x < a \text{ and} \tag{2.5}$$

$$y_1 = y_{1R} \quad \text{for } a < x < L_1 \tag{2.6}$$

where both y_{1L} and y_{1R} satisfy the homogeneous equation

$$m_1 \frac{\partial^2 y_1}{\partial t^2} - T \frac{\partial^2 y_1}{\partial x^2} + r_1 \frac{\partial y_1}{\partial t} = 0 \tag{2.7}$$

Matching conditions at x = a, the point at which the point force is applied, are

$$y_{1L} = y_{1R} \tag{2.8}$$

$$y'_{1L} - y'_{1R} = \frac{P}{T}, \tag{2.9}$$

where P is the magnitude of the harmonic load.

The boundary conditions at the two ends of the string are:

$$y_{1L} = 0 \quad \text{at } x = 0 \tag{2.10}$$

$$y_2 = 0 \quad \text{at } x = L \tag{2.11}$$

The problem has thus been reduced to solving three simultaneous second order ordinary homogeneous differential equations. The solutions are of the form

$$y_{1L} = [A_1 \sin(k_1 x) + B_1 \cos(k_1 x)]e^{i\omega t} \tag{2.12}$$

$$y_{1R} = [A_2 \sin(k_1 x) + B_2 \cos(k_1 x)]e^{i\omega t} \tag{2.13}$$

$$y_2 = [A_3 \sin(k_2 x) + B_3 \cos(k_2 x)]e^{i\omega t} \tag{2.14}$$

The coefficients in the above equations can be found by applying the six matching and boundary conditions. k_1 and k_2 are obtained from the dispersion relations, by substituting (2.12) and (2.14) in (2.7) and (2.2) respectively.

For the 40% coverage case shown in Figure 5, the PSD of a single fiber strain gauge, located 180 feet from the top, is shown in Figure 8. This is very near to the excitation point for the simulation model.

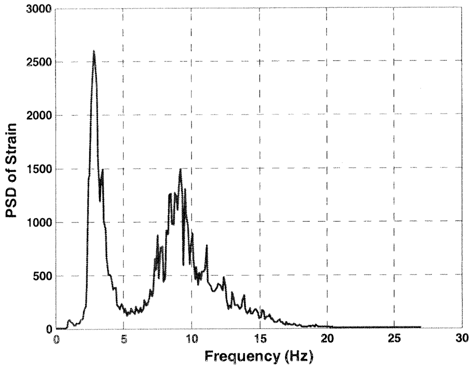

Figure 8 - PSD of Strain at 180 Feet from the Top, with 40% Strake Coverage.

In the PSD in Figure 8 the principal VIV peak is at 2.77 Hz. In the simulation, a 2.77Hz force was applied to a pipe with properties similar to the pipe tested in Gulf Stream. The applied force had a magnitude of 13.5 lbs, which was chosen to cause the predicted response to have approximately the same response amplitude as the measured response shown in Figure 5. The simulated response is shown in Figure 9. The excitation was applied at x = 180.45 ft as, shown in Figure 7. The curve shows the simulated response with strakes applied to the bottom 40% of the pipe from x = 290.4 ft to x = 484 ft. The top tension is set at 820 lb(3648N). The prescribed damping ratio for the bare pipe region is 0.01, and for the more strongly damped, straked region, the damping ratio has been based on equation(1.4). At 2.77 Hz the damping ratio is 0.067. The mass per unit length (including added mass) of the bare pipe is 0.0311(slugs/ft)(1.489 kg/m) and for the straked portion is 0.0777(slugs/ft)(3.72 kg/m). The diameter of the pipe is 1.4 in. Using the values given above for mass per unit length and tension, the speed of propagation in the bare and straked regions is 162.4 ft/s and 102.7 ft/s, respectively.

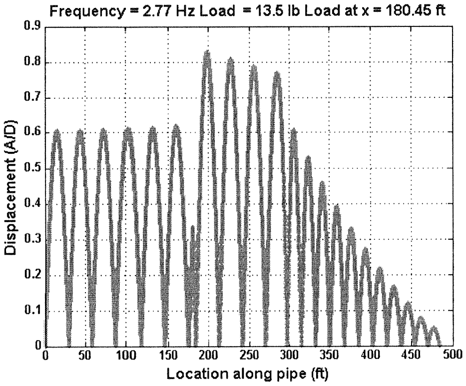

Figure 9 - Response amplitude for a pipe excited at 2.77 Hz with a 13.5 lb force at x = 180.45 feet from the top end.

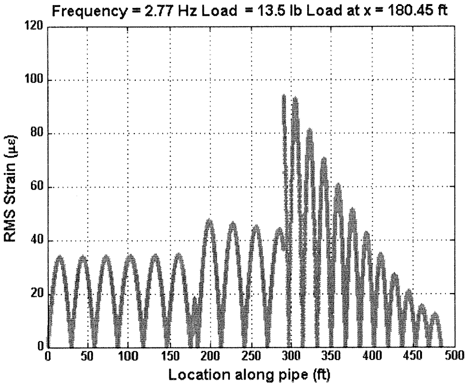

Figure 10 - RMS Strain for a pipe excited at 2.77 Hz with a 13.5 lb force at x = 180.45 ft.

The simulated RMS strain, corresponding to the displacement response shown in Figure 9, is given in Figure 10. The higher wave number in the straked region leads to an increase in strain at the point where strakes begin, due to lower bending wave speed.

Two mechanisms have been offered to explain the stress concentration observed in the measured strain, as shown in Figure 5. The first was a stress concentration due to wave reflection and the second is an increase in curvature in the straked region due to shorter wave lengths. Further study is required to fully explain the rise in strain at the interface. There is enough evidence to show that some care should be taken in designing the transition from bare to straked regions, so as to reduce regions of high strain at the boundaries.

Strain and Fatigue Damage Rate With and Without Strakes

In order to compare and evaluate the performance of strakes in sheared conditions, one must choose examples with similar current profiles. One such example is presented in Figure 11, which reveals three very similar profiles, one for each configuration tested:

- Bare pipe
- 40% coverage at the bottom
- 70% staggered coverage in five equal regions

In the cases shown, the stronger currents are at the bottom of the pipe. The sheared profiles vary from approximately 2.4 ft/s to 3.2 ft/s.

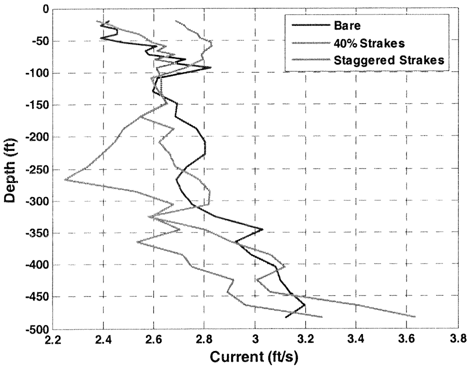

Figure 11 - Current Profiles for Comparison of the Bare Pipe Response to that with 40% and 70% Strake Coverage

Figure 12 shows the RMS strain measured for the second quadrant for each of the three straked configurations. The total strain as measured at any strain gauge is made up of contributions from bending as well as tension variations in the test pipe. To estimate true bending strain, one must subtract in the time domain the strain measured in one quadrant from that measured in the quadrant on the opposite side of the pipe. This results in common tension contributions in both fibers canceling one another, but allows common bending strains to add.

In this study, fiber optic mechanical failures greatly reduced the number of paired strained gauges, which were on opposite sides of the pipe. It was rarely possible to evaluate true bending. In order to salvage useful information from single fiber measurements, the data was filtered to eliminate the low frequency tension variations caused by vessel motion. Vessel heave, pitch and roll periods were in excess of 2 seconds and waves large enough to affect vessel motion had periods in excess of three seconds. In order to isolate bending energy from the tension variations due to vessel motion the data was high pass filtered at 1.0 Hz. VIV frequencies of interest were at 3 Hz and above. All data shown here has been high pass filtered.

When estimating damage rate, the data was also low pass filtered with a cutoff frequency of 24 Hz. This was done to prevent high frequency instrument noise from affecting the damage rate estimate and also to prevent aliasing. The sampling rate was 54 Hz for each strain gauge. With only bending related strain remaining in the filtered time series, estimates of dynamic bending strain could be made with single strain gauge measurements

Most of the dynamic strain data presented in this paper has been extracted from single gauge measurements, because, due to fiber failures, it was frequently not possible to take the difference between strain gauges on opposite sides of the pipe. Though disappointing, this was not entirely unexpected. The use of fiber optic strain gauges in this application was pushing the state of the art in the use of such gauges. A significant amount of valuable data was obtained, including gaining experience with a new measurement technology.

When comparing the RMS strain from a single fiber for the various coverages the bare case has the highest response, as expected.

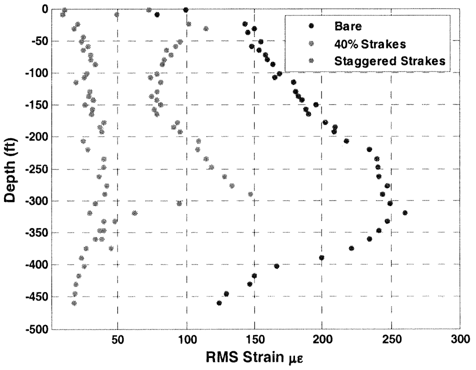

Figure 12 - RMS Strain in the Second Quadrant for Pipe with and without Strakes

The case with 40% strake coverage shows the previously described stress concentration at the point of reflection. For this particularly case the RMS single fiber strain is about half the RMS single fiber strain for the bare case at all locations, including the point of the stress concentration. The RMS single fiber strain for the staggered strake coverage is less than one-fifth that of the bare coverage case, and does not exceed 50 micro-strain ($\mu\varepsilon$) at any point on the pipe

The impact of the strakes can be seen not only in a reduction of RMS strain, but also in a change in frequency content. Figure 13 shows the PSD for each of the different strake configurations at an axial position 306 feet from the top. This depth is just inside the region with strakes in the 40%

case and is in a region without strakes for the 70% strake coverage case.

The Strouhal frequency response frequency for the bare case (the blue curve in Figure 13) is 4.48 Hz. The authors refer to the response peak at the Strouhal frequency as the 1X peak and the second and third harmonics as the 2X and 3X peaks. There is a clear 1X peak at 4.48 Hz. There is also a prominent 2X peak and a broad peak which includes significant energy at 3.0 times (3X) the Strouhal peak.

The 1X frequency for the 40% straked coverage case is 3.32 Hz. This is the green curve in Figure 13. There is also a small 3X peak. The frequency content of the response is changed by the strakes. The bare pipe case contains frequencies up to 25 Hz with significant energy up to 20 Hz. When 40% strakes are applied, the frequency content is limited to approximately 20Hz with significant energy up to 12 Hz. With 70% staggered strake coverage, the frequency content of the pipe is limited to 6 Hz at the location of this strain gauge with no visible 2X and 3X components.

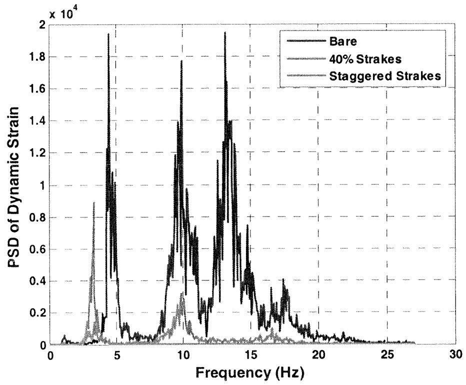

Figure 13 - PSD of the three configurations at 306 feet from the top

This change in frequency content due to the introduction of strakes has implications on the fatigue life of the pipe. Fatigue is influenced not only by the amplitude of the vibration, but also by the frequency of the vibration. The higher the frequency of vibration, the more strain cycles the pipe will be subjected to per unit time. Therefore the reduction or elimination of high frequency content in the cases with strake coverage will result in a reduction in the fatigue damage rate.

The damage rate for a stress history which is a narrow band, Gaussian, random process can be computed using equation(3.1), which is known as the Rayleigh damage rate formula. When the response has significant higher harmonic content as is the case here, the vibration response is not narrow-banded. Nonetheless the Rayleigh formula yields a conservative and reliable damage rate estimate, and is used in this paper for simplicity in making a point. The authors did compare the damage rate values to that obtained from the Dirlik method, which was specifically designed for the purpose of estimating damage rates for broad band spectra. The Rayleigh formula overestimates the damage rate by 5 to 20 percent, the difference being larger for broad band spectra and smaller for narrowband spectra. We use the Rayleigh formula here for purposes of simplifying the illustration.

$$D = \frac{V_0^+ T_{yr}}{C}\left(2\sqrt{2}S_{rms}\right)^b \Gamma\left(\frac{b+2}{2}\right) \qquad (3.1)$$

where the upcrossing frequency is defined as:

$$V_o^+ = \sqrt{\frac{\int f^2\, PSD(f)\, df}{\int PSD(f)\, df}} \qquad (3.2)$$

b and C are constants of the S-N curve which is defined as follows:

$$NS_r^b = C \qquad (3.3)$$

In equation(3.3), N is the number of cycles to fatigue failure and S_r is the bending stress range.

In the Gulf Stream tests the strains were measured directly and hence stress is computed by multiplying strain with the modulus of elasticity of the material. The bending strain data is high pass filtered, with a cutoff of 1 Hz to remove low frequency effects of the vessel motion, before computing the spectra for upcrossing frequency computation. The data is also low pass filtered with a cutoff of 24 Hz to prevent aliasing.

Damage rates are computed for an equivalent steel pipe, assumed to have identical dimensions, as the pipes tested at Lake Seneca and in the Gulf Stream, and having identical VIV response to the currents. The modulus of elasticity E is assumed to be 200 GPa(29E6 PSI).

For damage rate estimation in this paper b = 3.74 and C = 2.501E13. Here b and C correspond to an S-N curve commonly used by the industry called API-X' in which S_r values are in MPa.

For comparison purposes two tow cases from the Lake Seneca Test will also be used. One case was a 201 ft. bare pipe with a uniform current speed of 2.9 ft/s. The other case is a 201 ft. pipe with 100% strake coverage and a uniform current speed of 2.9 ft/s.

Figure 14 shows the spectra from the 201 ft. bare pipe case. The fundamental response frequency is 3.9 Hz for the cross-flow direction and 7.5 Hz in the in-line direction. Figure 15 shows the spectra for the fully straked test. The fundamental response frequency is 2.75 Hz in the cross-flow direction, and there is no dominant vibration in the in-line direction.

When comparing the cases of the bare pipe and fully straked pipe, the largest difference is the magnitude of the PSD. The bare pipe maximum spectral peak height is greater than 5000 times the maximum peak height for the fully straked pipe in the cross-flow direction.

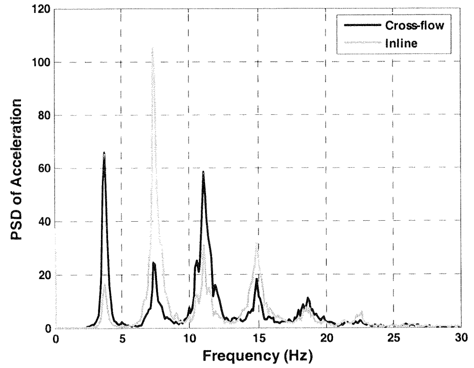

Figure 14 - Lake Seneca Bare Pipe Acceleration Spectra

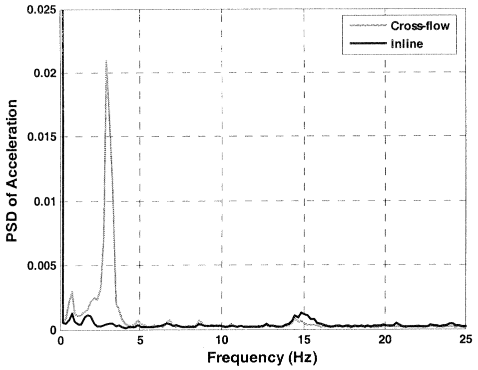

Figure 15 – Lake Seneca Pipe 100% Strake Coverage

For the Gulf Stream test, damage rate can be calculated directly using Equation (3.1) because strain was measured directly. At Lake Seneca, the acceleration response of the pipe was measured. We must therefore find a way of expressing strain in terms of acceleration for the Lake Seneca data. This is quite easy to do in the case that the transverse vibration of the pipe is tension and not bending stiffness dominated, which is true for the Gulf Stream and Lake Seneca tests.

From equation 2.1, but with damping or external excitation we can obtain the simple wave equation for the pipe.

$$\frac{d^2y}{dx^2} = \frac{1}{c^2}\frac{d^2y}{dt^2} \qquad (3.4)$$

Where c, the speed of propagation, is defined as:

$$c = \sqrt{\frac{T}{m}} \qquad (3.5)$$

By simply multiplying both sides of equation 3.4 by c^2 one arrives at an expression for acceleration in terms of the wave speed squared times the curvature.

$$c^2\frac{d^2y}{dx^2} = \frac{d^2y}{dt^2} = c^2 * curvature \qquad (3.6)$$

Therefore the rms stress may be expressed in terms of rms acceleration by means of the following expression:

$$S_{rms} = \frac{E * D_0}{2}\frac{m}{T}\ddot{y}_{rms} \qquad (3.7)$$

For the Lake Seneca test, the damage rate equation may be transformed to utilize acceleration measurements, directly. This transformation is derived in Reference (3) [Vandiver and Peoples 2003]. The derivation makes use of equation 3.7 and assumes that the pipe is tension dominated. Substituting the expression for rms stress from equation 3.7 into equation 3.1 leads to a Rayleigh damage rate expression in terms of rms acceleration:

$$D = \frac{\nu_o^+ T_{yr}}{C}\left(\sqrt{2}\, ED_o \frac{m}{T}\ddot{y}_{rms}\right)^b \Gamma\left(\frac{b+2}{2}\right) \qquad (3.8)$$

The damage rate for the 5 cases is presented in Figure 16. The Gulf Stream cases are presented as orthogonal x and y contributions, since cross-flow and in-line directions are not easily distinguishable, whereas the Lake Seneca cases have been rotated to distinct in-line and cross-flow directions. In Figure 16, if the legend says CF or IL, it means that the data is from Seneca. If the legend says X or Y the data is from the Miami tests. The Seneca tests are on pipes only 201 feet long, and therefore extend over a much shorter range of the plot in Figure 16.

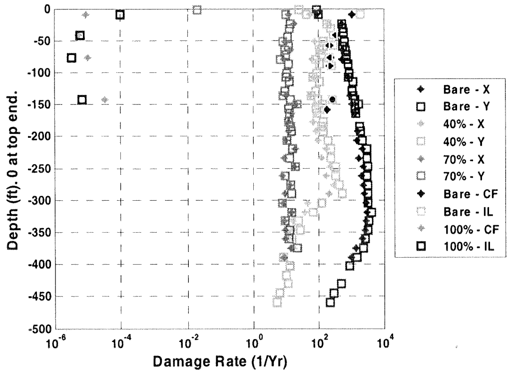

Figure 16 – Damage Rate Estimate for an Equivalent Steel Pipe with and without Strakes

Conclusions

The following characteristics of the damage rate can be clearly seen from Figure 16:

- Fully strake pipe has a damage rate which is eight orders of magnitude lower than that of bare pipe.
- The damage rate for the bare pipe is at least one or two orders of magnitude higher than the damage rate for the pipes covered partially with strakes.
- The damage rate is higher in the region with higher current speed for the bare pipe case.

- For the 40% coverage case the damage rate is approximately one order magnitude lower in the straked region than the bare region.
- For 40% strake coverage, the damage rate is higher near the point where the strakes begin than rest of the pipe because of the stress concentration at that point.
- For the 70% staggered strake coverage, the damage rate is almost uniform along the length of the pipe and is approximately one order of magnitude less than the 40% strake coverage case.
- The 70% staggered strake coverage eliminates all but the 1X peak and leads to damage rates which are two orders of magnitude less that the bare pipe.
- The 70% staggered strake coverage does not seem to have the stress concentration evident in the 40% case.
- The plot also shows that the damage rate in both the X and Y directions are almost the same (see the overlapping stars and squares for the bare and 40% strake coverage cases). Note that the X and Y direction here do not refer to the in-line and cross-flow directions but to the mutually perpendicular directions along which the strain was measured.
- The bare pipe from Lake Seneca was excited by uniform flow. The bare pipe test in the Gulf Stream was in sheared flow. Both the Gulf Stream and Seneca cases had approximately the same peak velocities. Both cases revealed damage rates which had approximately the same order of magnitude in damage rate.

More generally, the results of these tests show that strakes reduce not only the amplitude of vibration, but also the frequency content of the vibration at high mode number.

Long regions of bare pipe adjacent to long straked regions lead to stress concentrations, which may need to be avoided by creating a more gradual transition from bare to straked pipe.

Further testing should be done to optimize staggered location strategies for strakes and also to optimize the percent of desired coverage.

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Nomenclature

A	*Wave amplitude[length]*
b	*A material parameter that characterizes the slope of a fatigue S-N curve [-]*
c, c_1, c_2	*Speed of Propagation [length/time]*
C	*Material Parameter that characterizes the slope of the fatigue SN curve [stress^b]*
D	*Damage Rate [time^{-1}]*
D_o	*Outer Diameter [length]*
E	*Young's Modulus [force/length^2]*
f	*Frequency [s^{-1}]*
I	*Cross-section Area Moment of Inertia [length^4]*
k_r	*Wave Number [length^{-1}]*
L	*Length of Pipe [length]*
m	*Mass per Unit Length [mass/length]*
n	*Mode Number [-]*
r_1 & r_2	*Damping constants[force/length/velocity]*
S_{rms}	*RMS Bending Stress [force/length^2]*
T	*Tension [force]*
T_{yr}	*Number of seconds in a year [time]*
ν_+^0	*U-Crossing frequency [time^{-1}]*
y	*Transverse Vibration Amplitude of the Pipe*
$\ddot{y}_{rms}$	*Root Mean Square Acceleration [length/time^2]*
ζ	*Damping Ratio [-]*
Γ	*Gamma Function [-]*