

OMAE2009-79757**AN EXPERIMENTAL EVALUATION OF VORTEX-INDUCED VIBRATION OF A RISER BUNDLE WITH GAPS****J. Kim Vandiver**Massachusetts Institute of Technology
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Houston, Texas, USA**ABSTRACT**

VIV model test results are presented for a bundle of three parallel pipes all lying in the same plane, similar to a riser with large kill and choke lines. The rigid model was attached to a spring-mounted frame in the MIT towing tank. The horizontal model was towed in the tank and allowed to respond in free vibration to vortex-induced vibration in the cross-flow direction. The angle of attack of the model was varied from 0 to 90 degrees. The model was tested with and without helical strakes. Without strakes the model exhibited significant vibration at 0 and 90 degrees angle of attack. Strakes suppressed VIV at all angles of attack.

INTRODUCTION

The principal purpose of this model test was to establish whether or not the as-built prototype riser would likely exhibit any undesirable flow-induced vibration characteristics, and to determine if strakes suppress any undesirable VIV. The model was configured so as to test for vortex-induced vibration and for high mean lift coefficients that might contribute to galloping or flutter behavior.

Deep Ocean Mining Project Description

The Nautilus Minerals Solwara I field development is located approximately 50 km North of Rabaul in the eastern extent of the Manus Basin – Bismark Sea, New Ireland Province, Papua New Guinea (PNG). This ore deposit consists of a massive

sulphide mineralization of copper, zinc, gold and silver, and is in the Exclusive Economic Zone of Papua New Guinea. The seabed ore will be excavated into particle sizes less than 50 mm (2 inches) in diameter by a Seafloor Mining Tool located on the seabed. The ore will be fed through a 155 m (508 ft) long flexible pipe jumper to a subsea slurry lift pump which will be suspended at the end of a vertical steel riser. The slurry will then be pumped to the surface through the vertical steel riser, which will be suspended from the mining service vessel. The vertical steel riser is subject to current, which may cause flow-induced vibration. The ore will be dewatered and the waste water will be mixed with fresh sea water, pressurized, and pumped through the water injection lines to power the subsea slurry lift pump. The waste water used to drive the subsea pump will be discharged from the subsea pump to the sea floor level.

Model Description

The prototype vertical riser bundle consists of three parallel cylinders all lying in the same plane. The middle steel lift pipe is 13.625 inches in diameter. This main pipe is flanked by two 8.625 inch steel water injection lines, with a gap of 4.57 inches between the risers. The full scale riser is intended to operate in a near vertical hang-off arrangement several thousand feet in length. The riser is assembled from joints approximately 62 feet in length. The three pipes are held in position relative to one another with clamps at each joint and with additional centralizers, spaced approximately 20.7 feet apart. The purpose of the model test was to see if this vertical steel riser

bundle would exhibit VIV or would generate significant lift and drag forces.

The approach used in this test was to construct a spring mounted model of a rigid short section of the riser bundle. The scale factor for the riser diameters was 1 to 7.16. The model of the central main pipe had a diameter of 1.903 inches and a length of 78 inches, which resulted in a model which had a length to diameter ratio of 41. The model was therefore equivalent to about two thirds of the length of one riser joint. The following terminology is used in this paper. The large central pipe is referred to as the main pipe. The two smaller pipes are referred to as the water injection lines. The term riser or riser system, means the assemblage of the three pipes which make up the vertical riser.

The model was fixed horizontally between two struts. The struts attach to a horizontal girder which is connected by springs to the towing carriage. The model, struts and girder complete a box structure which is free to move vertically on linear bearings. This structure acts as a single degree of freedom oscillator, responding in the cross-flow direction only. The model was constructed so that the angle of incidence of the flow could be adjusted with respect to the plane defined by the two water injection lines and the main pipe. The riser looks a little bit like a symmetric airfoil. The model tests included measurements of VIV for the model with and without protective helical strakes wrapped around the main pipe. Mean lift and drag forces were also measured.

The critical dimensions from the point of view of this model test were the external diameters of the main pipe and the water injection lines and the gap between the injection lines and the main pipe. A prototype to model scale factor of 7.16:1 was selected based on the availability of carbon fiber tubing of suitable diameters and the capacity of the carriage in the towing tank. Carbon fiber tubing was selected because of its high stiffness to weight ratio and its resistance to corrosion when immersed in water. The key dimensions of the model were 1.903 inches in diameter for the main pipe, and 1.203 inches for the water injection lines. The gap was 0.638 inches. The riser model, installed in the towing tank, is shown in Figure 1, and the model and full scale properties are summarized in Table 1.

The full scale riser has a clamp at each joint which holds the three pipes in place. The equivalent clamp on the model was patterned after the full scale one, but for practical reasons was not made exactly to scale, so as to facilitate model test functions, such as being able to easily change the angle of attack of the model. The differences are so small as to have negligible effect on the model tests.

Figure 2 shows the model clamp with the three carbon fiber risers connected to it.

No attempt was made to model the density or stiffness of the real riser system or to model directly any specific mode of vibration. The main pipe model was made of thin-walled carbon fiber composite. The ends were plugged with machined PVC plugs with O-ring seals. The inside of the tube was air filled. The PVC plugs had a 3.5 inch diameter flange, which extended beyond the 1.9 inch diameter main pipe. The flange has two arcs of small holes which were used to align the angle of attack of the riser with the flow. A centering hole was machined on the outside ends of both PVC plugs. This hole mated with a mounting pin on each of the struts. A slot in the end cap perpendicular to the hole engaged a pin on the strut which prevented rotation, as shown in Figure 3.

The model water injection lines were also made from carbon fiber tubing. They were attached to the clamps at each end. The clamp could be rotated relative to the main pipe in increments of 7.5 degrees from 0 to 90 degrees. By rotating each end by the same amount in the same direction, the angle of attack of the plane defined by the main pipe and the two water injection lines, could be changed. Hence an angle of attack of 0 degrees corresponded to the plane of the riser being parallel to the direction of flow. At a 90 degree angle of attack the plane of the riser was perpendicular to the flow.

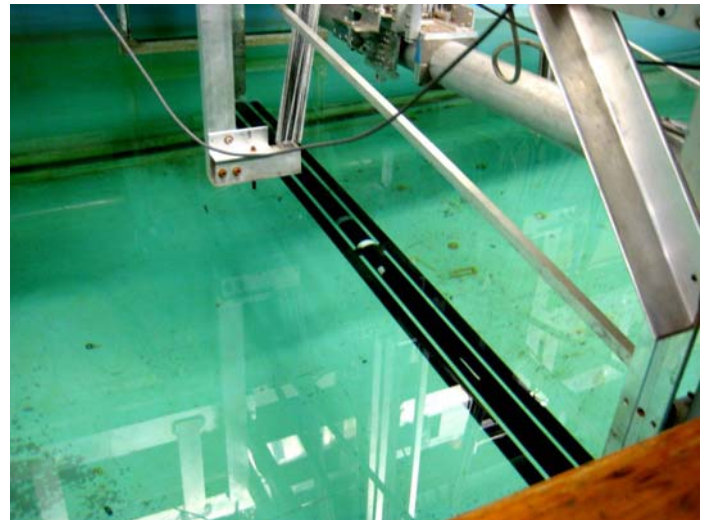


Figure 1. Carbon fiber model installed on the carriage



Figure 2. Model riser clamp with carbon fiber main pipe and water injection lines. The screw is for setting the angle of attack.

If the fixtures were rotated by the same amount but in opposite directions, a twist was introduced in the injection lines with respect to the main pipe. In other words, the injection lines wrapped around the main pipe in a very gradual helix. Two test cases were conducted in which plus and minus 7.5 degrees and plus and minus 15 degrees of twist were used. This gave a total twist of 15 and 30 degrees respectively over the length of the model, which was 41 diameters long. At full scale this would correspond to twists of 20 and 40 degrees, respectively, over the length of one 62 foot riser joint.



Figure 3. Gray PVC end plug with central mounting hole and anti-rotation slot. The circle of small holes was used to set the angle of attack of the model riser relative to the incoming flow.

At the center of the model span there were small rubber spacers, which prevented relative motion between the main

pipe and the two water injection lines. This would be the function of centralizers on the prototype. The unsupported span of the injection lines on the model was about 20 diameters, which corresponds to the distance between centralizers or centralizers and clamps on the full scale riser. The centralizers have an important role at both model and prototype scale. They reduce the unsupported length of the injection lines, which increases the lowest natural frequency of the span to well above the vortex shedding frequency, thus preventing VIV of the injection lines.

EXPERIMENT DESCRIPTION

Mass ratio, natural frequency and reduced velocity

The test facility has the capability to test a spring-supported rigid cylinder as shown in Figure 4, a photograph of the test carriage with the model of the bare main pipe in place. The model is connected to a rigid frame which is able to move vertically. The moving frame is supported by linear springs. The total mass of the riser plus moving frame is more than 30 Kg. This results in a ratio of moving mass to mass of water, displaced by the cylinder of approximately 8.48 to 1.0. The mass ratio of the prototype main pipe is 2.31:1. The consequence of the model having a much higher mass ratio is that the band of speeds over which lock-in is exhibited on the model will be narrower than on the prototype. Care was taken to test the model at the correct critical reduced velocities, so as to achieve maximum response.

The natural frequency, f_n , in water of the main pipe and framework is approximately 1.86 Hz. This system exhibited maximum vortex-induced vibration when the forward speed, U , produced a nominal reduced velocity, V_m , of approximately 5.6 to 6.0. The nominal reduced velocity is defined in Equation 1 where D is the diameter of the main pipe.



Figure 4. Tow carriage with model of the bare main pipe

$$V_m = \frac{U}{f_n D}$$

$$\text{For } f_n = 1.86 \text{ Hz and } D = 0.0483 \text{ m}$$

$$\Rightarrow V_m = 11.13 * U \text{ (m/s)}$$

Equation 1

Riser properties	Prototype	Model
Riser length(ft)	5000	6.5
Outside diameter of main pipe(inches)	13.625	1.903
Inside diameter of main pipe(inches)	12.125	1.727
Outside diameter of injection lines(inches)	8.625	1.203
Inside diameter of injection lines(inches)	7.625	0.930
Gaps between pipes(inches)	4.565	0.638
Main pipe effective mass ratio	2.31	8.48
Other as built properties of the actual model		
Main pipe and injection lines were carbon fiber epoxy composite. The L/D of the model was		41.09
Length of main pipe without end fittings(inches)		78.188
Dry Mass of main pipe with end fittings(Kg)		1.33
Dry Mass, main pipe with end fittings and strakes(Kg)		1.35
Dry Mass, 2 injection lines, end fittings & clamps(kg)		2.48
Dry Mass of complete riser system(Kg)		3.83
Dry Mass of complete riser system+strakes(Kg)		3.85
Total moving mass of frame + bare main pipe (Kg)		30.896
Mass of water displaced by the main pipe(Kg)		3.644
Ratio of moving mass to displaced mass of the main pipe-defined as the mass ratio		8.48
Total vertical spring constant (N/m)		4718
Natural frequency of the bare main pipe in air(Hz)		1.97
Natural frequency of the main pipe in still water(Hz)		1.86
Natural frequency of the riser system in still water(Hz)		1.72

Table 1. Model and prototype properties

When the water injection lines were added to the model, the natural frequency in water was reduced to about 1.72 Hz, which is close enough to that of the bare main pipe, that the model test matrix planning could be based on the hydrodynamic characteristics of the model bare main pipe without injection lines. Figure 5 shows a photograph of the model, complete with injection lines, installed in the towing carriage.

Damping of the model and framework

The springs and the linear bearing that support the moving frame introduce considerable damping. This damping has been measured and an active control system has been designed and

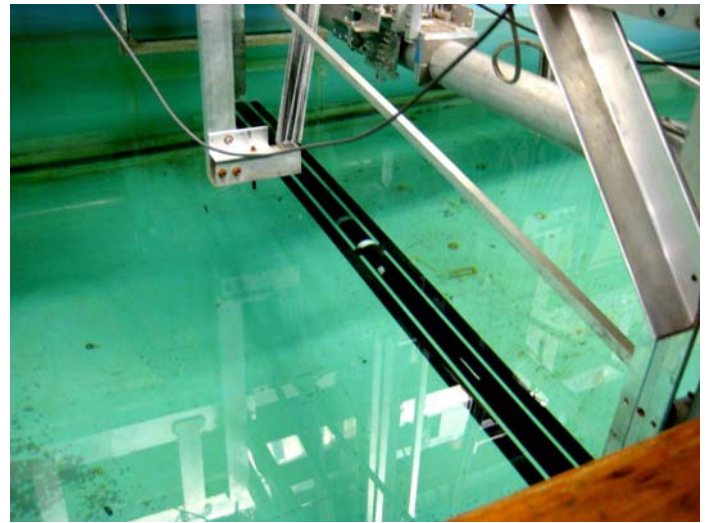


Figure 5. Model riser at zero angle of attack, installed in the carriage.

constructed to actuate a linear motor which applies a cross-flow exciting force in phase with cylinder velocity. This external excitation compensates for the system structural damping. Without the feedback the damping is in excess of 6% of critical damping. With feedback, the damping is reduced to about 1.5% of critical, as measured in still water on a single bare cylinder. At the beginning of every run the model was given an initial displacement and released. This accomplished two things. The first was an opportunity to observe the apparent in water damping of the system and the second was to guarantee that VIV was not prevented by high static damping. Without the initial push, it was possible that VIV would not happen because the initial breakout force was not achieved.

Displacement, lift and drag force measurements

The MIT towing carriage was previously fitted with lift and drag force sensors, which are built into connectors between the struts and the model. These sensors were not optimized for these tests. They were calibrated by hanging weights directly on the riser in the lift direction. In the drag direction the calibration weights were applied to the riser by means of a horizontal string, which was tied to the riser and then passed over a pulley to the hanging weight. Neither lift nor drag measurements were of high precision, but the results provide useful corroboration of the VIV measurements, which were the primary objective of the tests.

The overall accuracy in the drag direction was approximately plus or minus 15% in the estimated drag coefficient. This reflects errors introduced by misalignment of the calibration string and pulleys, pulley friction and transducer noise. The primary source of error in lift force is due to static friction in the spring support system. The total spring constant for the system was 4718 N/m. Static friction caused the equilibrium point of the system to vary by approximately plus or minus 3

mm, which corresponds to an offset error in lift force of approximately plus or minus 14 N.

This is illustrated in Figure 7, which shows the RMS and mean A/D response of the bare cylinder as a function of reduced velocity, V_m . The RMS maximum is 0.7 diameters, which corresponds to about two diameters peak to peak. This is the expected response of a lightly damped spring mounted cylinder under maximum response, lock-in conditions. The mean response would normally be expected to be zero. Instead it varies by 0.1 diameters over all the results plotted. This leads to an uncertainty in computed lift coefficient on the order of 0.5 in the reduced velocity range of 5 to 8. This is substantial and will have to be taken into consideration when interpreting the lift coefficient data. Nonetheless, the relative comparisons of mean lift and drag coefficients presented here reveal valuable insights as to the behavior of riser bundles at various angles of attack.

The cross-flow displacement of the model was measured by a direct displacement transducer attached to the frame. It is a type of transducer known as a linear variable transformer. The displacement measurement is accurate to approximately 1 mm, which corresponds to 2% of the model pipe diameter. Estimates of RMS A/D response to VIV are therefore quite reliable, because they are computed with respect to a statistical mean.

Modeling with strakes

The triple strakes were modeled with a flexible foam material, with a rectangular cross-section, as shown in Figure 6. The height was set at 0.48 inches, or 25% of the main pipe diameter. The thickness was 0.375 inches. The pitch was 17.5 diameters. Since the riser model was 41 diameters in length, the strakes made 2.33 complete wraps of the main pipe over the length of the model. The foam strips came with a self-adhesive backing. The adhesive performed reasonably well in water, though by the end of the test the strakes had begun to come loose in a few places. The strakes were held in place at intervals of three to four diameters with tie wraps, which are similar to the straps and clamps used on full scale risers to fasten strakes in place.

Although not an exact scale model of the strakes intended for the full scale prototype, these model strakes were completely effective in eliminating VIV on the bare main pipe without the water injection lines. The model strakes did have the same height and pitch as the full scale ones. The strakes were made of very low density foam and had a total mass of 0.020 kg, which was negligible compared to the moving mass of the system.

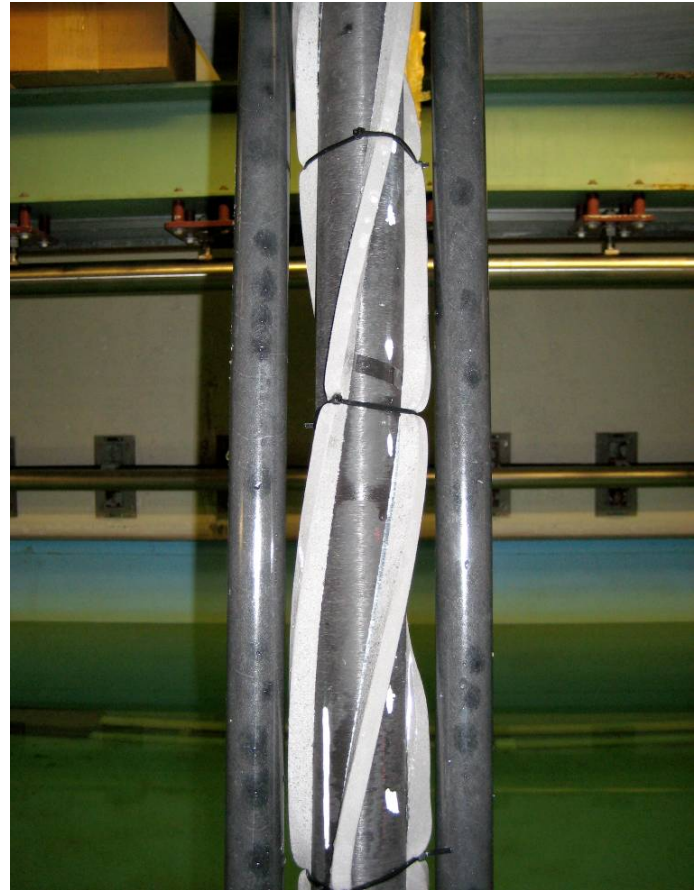


Figure 6. Model riser with strakes, Height = 0.25D, Pitch = 17.5D

Model scaling principles

The modeling approach was to test all configurations of interest over a reduced velocity range which would pass through the range which would include potential lock-in behavior. The MIT test apparatus has a limit on maximum carriage speed of approximately 1.5 m/s. The test cylinder diameters and the spring stiffness supporting the moving framework were chosen so as to make it possible to test over a range of reduced velocities, which included the values favorable to VIV. The principal modeling assumption being made is that the real riser will exhibit similar VIV when exposed to the same range of reduced velocities.

A second modeling assumption is that the behavior observed in the model will not change because of Reynolds number, when predicting the full scale behavior. The Reynolds number is given by the following equation.

$$R_e = \frac{DU}{\nu}, \text{ where } \nu \text{ is the kinematic viscosity} \quad \text{Equation 2}$$

It happens that the velocity range used in the tow tank from 0.3 to 1.5 m/s is about the same as the expected full scale currents. The kinematic viscosity of water is approximately the same for model and prototype, and therefore the ratio of Reynolds number from full scale to prototype is about the same as the ratio of diameters, which was 7.16, the scale ratio for the model. When a typical model Reynolds number was 50,000 the corresponding full scale value would be 358,000. This unfortunately crosses the boundary between sub-critical and supercritical flow. There is considerable uncertainty in scaling up model test results for VIV when the Reynolds numbers between model and full scale cross this boundary. The uncertainty is the greatest in predicting the critical reduced velocities and the VIV response amplitude to be expected. Until we have much more high Reynolds number data, we must accept this uncertainty in predicting the full scale behavior.

The full scale riser has many different natural frequencies which span a wide range of potential VIV frequencies. In this model test no attempt was made to model any particular full scale natural frequency. It is expected that the worst case response of the full scale riser will be when any particular natural frequency leads to coincidence with a critical reduced velocity as observed in the model tests. Hence, these model tests represent a worst case scenario corresponding to a uniform, uni-directional current, applied to a substantial length of the prototype riser.

RESULTS

Many different configurations were tested, which included the bare riser with and without strakes, and the riser bundle with and without strakes. The riser bundle with and without strakes was tested at various angles of attack. In addition the riser bundle without strakes was tested with two angles of twist in the injection lines. In all more than 250 individual runs were made. Table 2 shows the various configurations that were tested. At each configuration, 10 to 20 different individual towing speeds were used. The table also summarizes whether or not VIV was observed and whether or not non-zero mean lift was measured.

The bare main pipe was tested to serve as a baseline VIV case. There is an abundance of single cylinder data in the known literature. The bare cylinder test was done to verify that the test technique was yielding the expected VIV amplitude for a bare, spring-mounted cylinder. This bare cylinder was also tested with the 25% helical strakes. This test verified that the strakes were effective at suppressing VIV on the bare cylinder, as has been reported elsewhere in the literature.

Occurrence of observed VIV or non-zero mean lift	VIV	Mean lift
1. Bare main pipe	Yes	No
2. Bare main pipe with strakes	No	No
3. Riser without strakes, $\alpha = 0$ degrees	Yes	No
4. Riser at $\alpha = 7.5, 15, 22.5$ degrees	No	Yes
5. Riser with strakes at $\alpha = 0$ & 90 degrees	No	No
6. Riser without strakes at $\alpha = 90$ degrees	Yes	No
7. Riser with a total twist of 15 degrees	Yes	No
8. Riser with a total twist of 30 degrees	No	No
9. Riser with strakes, $\alpha = 0, 15, 45$ & 90 degrees	No	No

Table 2 Model test configurations with a summary of qualitative results. α is the angle of attack of the riser.

The presentation of results is organized by configuration. Each configuration is described separately below. The bare cylinder data is discussed first, so as to establish a baseline for behavior. All lift and drag coefficients in this report are based on the reference diameter of the main pipe. The drag and lift coefficients are defined in Equation 3.

$$C_D = \frac{F_{drag}}{\frac{1}{2} \rho_w U^2 DL}, \quad C_L = \frac{F_{lift}}{\frac{1}{2} \rho_w U^2 DL} \quad \text{Equation 3}$$

Bare cylinder VIV response

Figure 7 shows the RMS cross-flow response of the bare main pipe model as a function of reduced velocity, V_m . The peak RMS response is approximately 0.7 diameters, which would be about 2 diameters peak to peak. This is as expected for a lightly damped spring mounted single cylinder at lock-in. The reduced velocity in all figures is based on a natural frequency in still water of 1.86 Hz. The peak response occurred at a reduced velocity of 6.0. Figure 8 is the observed response frequency versus reduced velocity for the bare main pipe.

Drag coefficient for the bare cylinder, straked bare cylinder, and riser.

Figure 9 is the mean drag coefficient as a function of reduced velocity for the bare main pipe, straked main pipe and for the riser bundle at 0 and 90 degrees angle of attack. The bare main pipe peak C_d is approximately 4 at a reduced velocity of 6. This is somewhat higher than expected from other VIV published drag coefficient data for single cylinders experiencing large amplitude VIV. The explanation may be in part due to the relatively large force calibration errors associated with the apparatus. The overall trends are consistent with VIV, such that large amplitude VIV leads to amplified mean drag coefficients.

The straked main pipe had a measured C_d of approximately 2.3, which is about half that of the vibrating bare riser but greater than the stationary bare cylinder, all of which are consistent with the literature. Reference 2[Vandiver et al, 2006] provides measured flexible cylinder data from recent tests with and without helical strakes.

The drag coefficient on the riser is maximum, as expected, at a 90 degree angle of attack. Note that in all cases the reference diameter is that of the bare main pipe. It is not surprising that at an angle of attack of 90 degrees, the riser would exhibit a C_d in excess of 5. As will be shown later, there is also substantial VIV at this angle of attack.

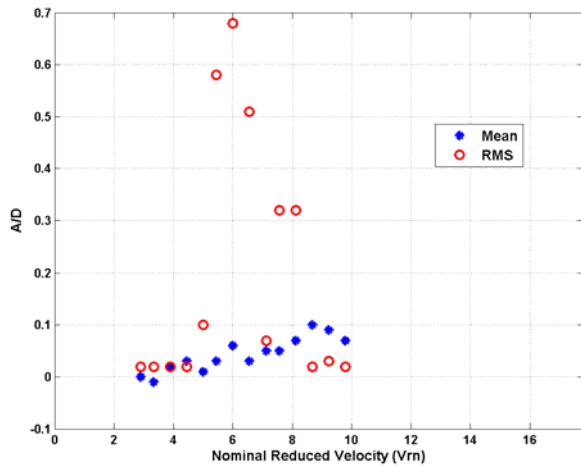


Figure 7. Bare main pipe, RMS A/D and mean A/D versus reduced velocity.

Bare cylinder response, with strakes

Figure 10 shows the RMS response of the bare cylinder with the 25% high strakes. The response is so small that it cannot be distinguished from the background noise of the displacement transducer. The strakes are very effective for this model. Strakes have an associated drag penalty as shown in Figure 9, which shows the mean C_d versus reduced velocity. It is approximately 2.3, which is twice that of a stationary cylinder, but substantially less than the C_d for a vibrating bare cylinder.

Response of the riser as a function of angle of attack—no strakes.

After completion of the bare main pipe baseline measurements, the testing turned to the riser system of three pipes. The principal objective was to determine if the riser exhibited any VIV behavior at various angles of attack. A secondary objective was to measure the mean lift coefficient for angles of attack between 0 and 90. Mean lift is expected when the angle of attack is different from zero and is due to airfoil behavior. It is not a result of VIV.

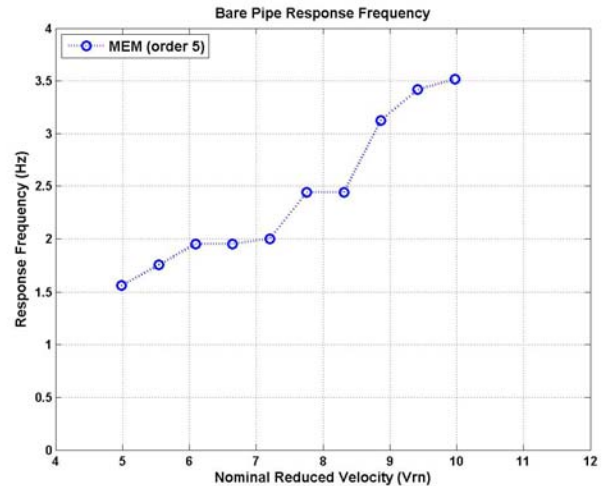


Figure 8. Bare main pipe response frequency versus nominal reduced velocity. (Maximum entropy method, 5 pole auto regressive spectral analysis).

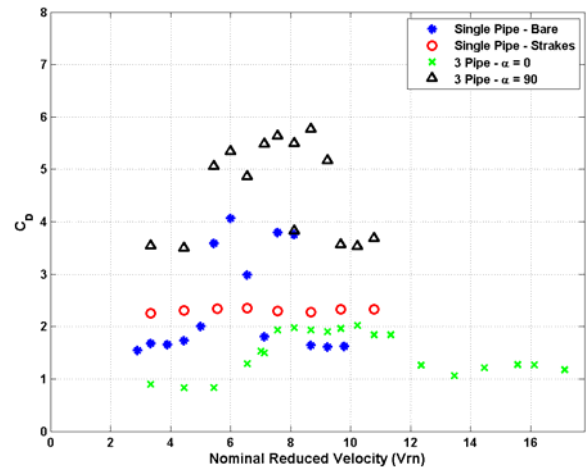


Figure 9. Drag coefficients for bare and straked main pipe and for the riser at 0 and 90 degrees angle of attack versus V_{rn}

For these tests an angle of zero is defined as when the plane of the three pipes, which make up the riser, is parallel to the flow. Tests were conducted at 0, 7.5, 15, 22.5, 30, 45, 60, 75 and 90 degrees angle of attack. VIV was observed at only 0 and 90 degrees.

Figure 11 shows the RMS A/D for the riser at angles of attack between 0 and 90 degrees. The response was negligible, except

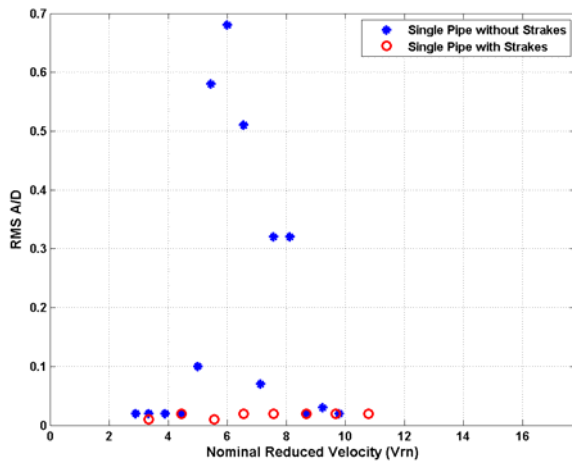


Figure 10. Comparison of RMS A/D for main pipe with and without strakes.

at 0 and 90 degrees. At these two angles of attack the RMS response was approximately 0.55 diameters. This suggests that the riser is most vulnerable to VIV at 0 and 90 degrees angle of attack. The addition of strakes will be shown to remedy that problem. Figure 12 shows the mean C_d for the riser at the same angles of attack. The C_d was computed in all cases using the diameter of the main pipe as the reference. Except at 0 and 90 degrees the C_d increases with angle of attack. At 0 and 90 there is an unusual increase in C_d , which results from the large amplitude VIV at those angles of attack, as seen in Figure 11. Although the addition of strakes eliminates VIV it does not reduce the drag coefficient on the riser by much. In fact it broadens the reduced velocity range over which the C_d stays constant, as shown in Figure 16.

Figure 13 shows the mean lift coefficient for the same range of angle of attack. Note that in these tests, the maximum lift coefficient corresponds to 15 degrees angle of attack. At this angle the mean lift coefficient is approximately 1.5 ± 0.5 . The lift coefficient diminishes at all larger angles of attack. Note that the lift coefficient at 0 angle of attack is approximately 0.25. It should in theory be zero. This offset is an illustration of the bias error in the mean transverse deflection that is caused by high static friction in the system. The mean lift coefficient at its largest is less than the drag coefficient at all angles of attack. With a large enough lift coefficient, the riser might deflect slowly to one side in a current and might possibly gallop. This study did not investigate potential galloping behavior.

Figure 14 Shows the VIV response for the only configurations which yielded non-zero response, including the bare main pipe and the riser at 0 and 90 degrees angle of attack. At all other angles of attack the VIV response was zero.

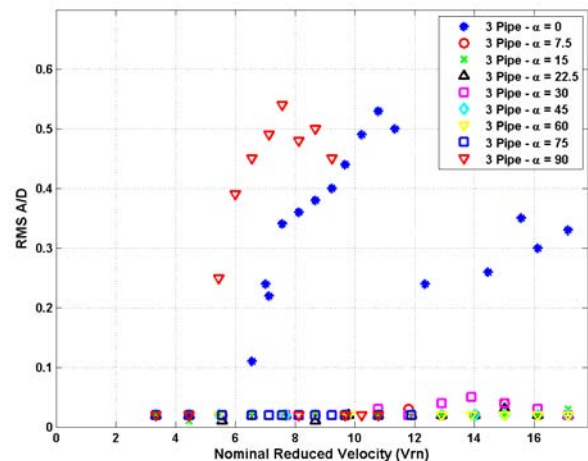


Figure 11. RMS A/D versus reduced velocity for the riser as a function of angle of attack.

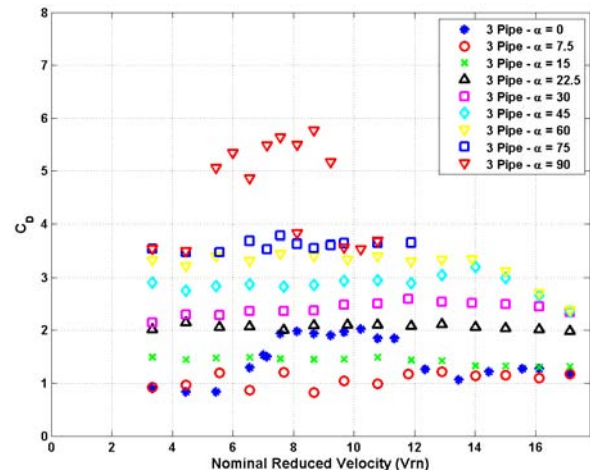


Figure 12. Mean C_d , based on the main pipe diameter, for the riser for angles of attack from 0 to 90 degrees, versus reduced velocity.

Because the maximum measured lift coefficient for the riser was observed at an angle of attack of 15 degrees, it was decided to also test at 7.5 and 22.5 degrees of angles of attack. Figure 13 shows that the mean lift coefficient at 7.5 degrees is less than at 15 degrees. The same is true at 22.5 degrees. The worst case mean lift was measured at an angle of attack of 15 degrees. Figure 15 shows the mean A/D for 7.5, 15 and 22.5 degrees angle of attack. As expected the case with the maximum lift coefficient, 15 degrees, corresponds to the greatest mean transverse deflection. The deflection steadily increases with flow speed for all three angles of attack. At these angles of attack the riser acts like a poorly performing wing.

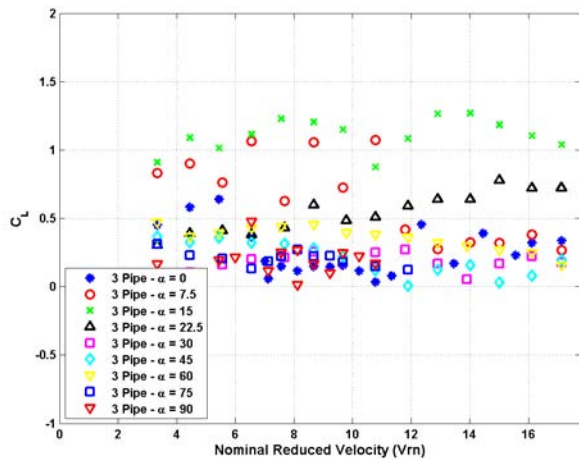


Figure 13. Mean lift coefficient, based on the main pipe diameter, for the riser for angles of attack from 0 to 90 degrees, versus reduced velocity.

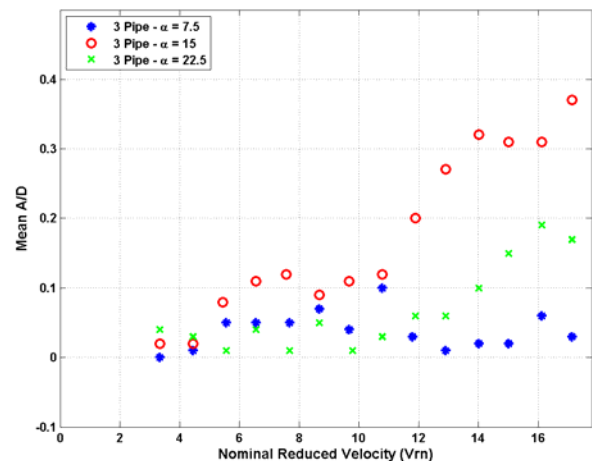


Figure 15. Mean A/D for the riser system at 7.5, 15 and 22.5 degrees angle of attack.

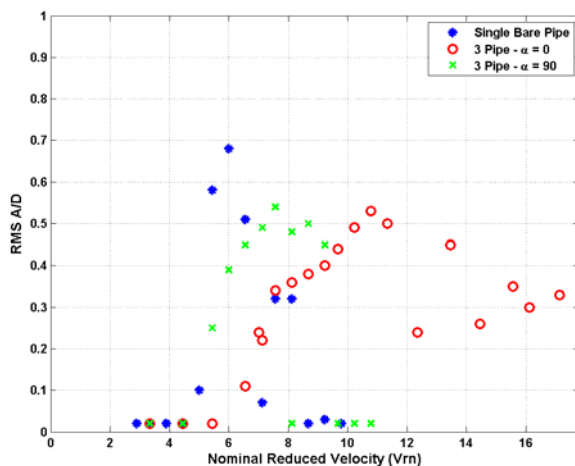


Figure 14. RMS A/D for the bare main pipe and for the riser at 0 and 90 degrees angle of attack.

Response of the riser with strakes, as a function of angle of attack

It has been shown that the riser exhibited VIV only at 0 and 90 degrees angle of attack. With the addition of strakes, VIV was not observed at any angle of attack, as is shown in Figure 18. The addition of strakes does not affect the mean drag coefficients of the riser bundle to any significant degree, as can be seen in a comparison of Figure 16 and Figure 12. As in all cases, the coefficients shown in the figures are based on the diameter of the main pipe.

The lift coefficient with strakes at various angles of attack is shown in Figure 17. The maximum mean lift coefficient is approximately 1.5 at 45 degrees angle of attack.

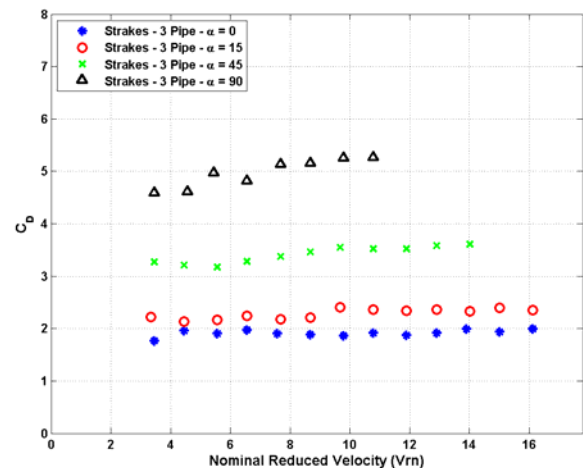


Figure 16. Drag coefficients for the riser system with strakes at various angles of attack, versus reduced velocity.

A few tests were conducted to investigate whether or not a small helical twist in the injection lines would improve the VIV performance. Two specific tests were conducted in which the total twist over the length of the model was set at 15 and 30 degrees. For the 15 degree twist, the fixture on the starboard end of the model was rotated up 7.5 degrees and the port side was rotated down by the same amount. In the 30 degree test the amount of twist was changed to 15 degrees up on the starboard and 15 degrees down on the port end. The average angle of attack was kept at zero. Figure 19 shows the RMS A/D, Figure 20 shows the C_d and Figure 21 shows the mean lift coefficient for the cases with twist.

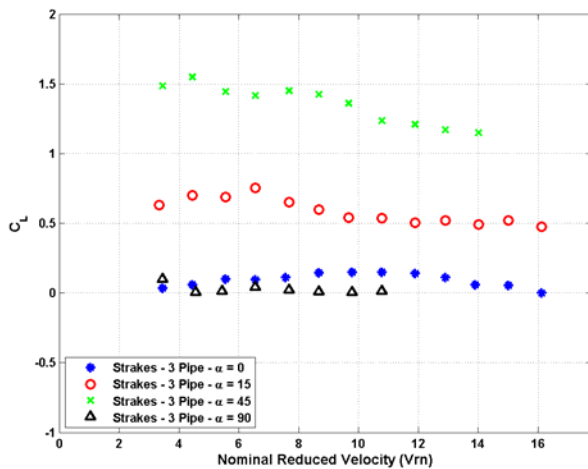


Figure 17. Lift coefficient for the riser system with strakes at various angles of attack, versus reduced velocity.

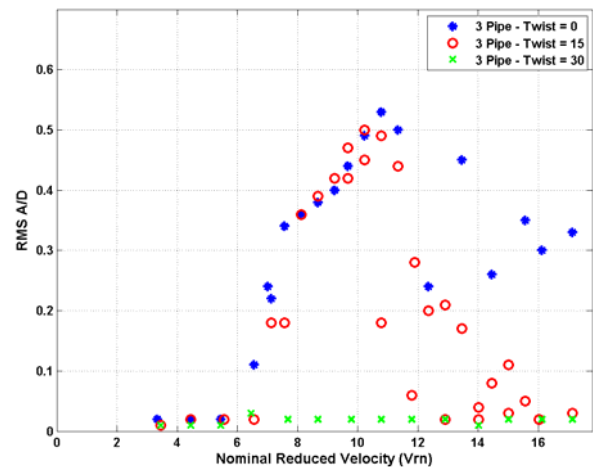


Figure 19. RMS A/D for the riser system with 0, 15 and 30 degrees of injection line twist, versus reduced velocity.

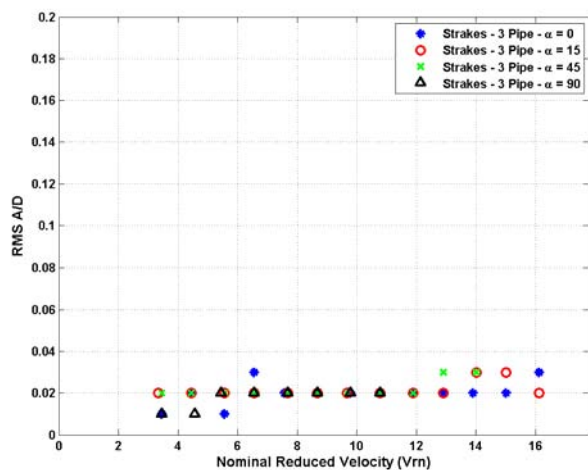


Figure 18. RMS A/D of the riser system with strakes at various angles of attack, versus reduced velocity.

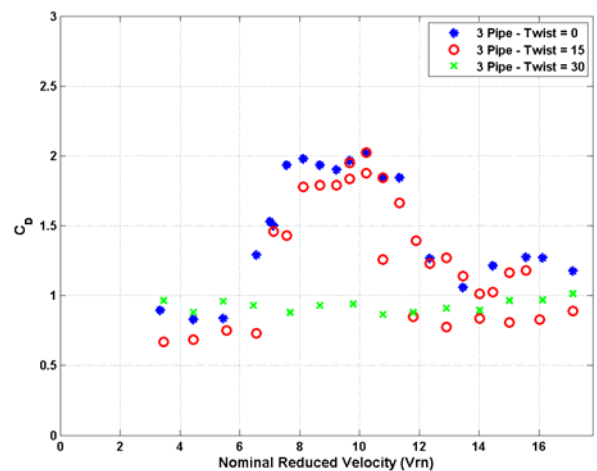


Figure 20. Mean C_d for the riser system with 0, 15 and 30 degrees of injection line twist, as a function of V_{rn} .

The mean lift should be zero as the twist was symmetric about zero degrees angle of attack. All of the values shown in Figure 21 are within the expected error bounds for measured lift coefficient as established during the system calibration. Recall that at zero angle of attack there was considerable VIV, as per Figure 11. With 15 degrees of total twist the peak VIV was the same. At 30 degrees total twist VIV was absent. The conclusion to be drawn is that arranging the injection lines in a helix does help to suppress VIV. However, the amount required to fully suppress VIV is probably impractical to manufacture, to store on board ship and to assemble. The test with 30 degrees of twist over the length of the model corresponds to 40 degrees of twist over the length of a 62 foot long riser joint.

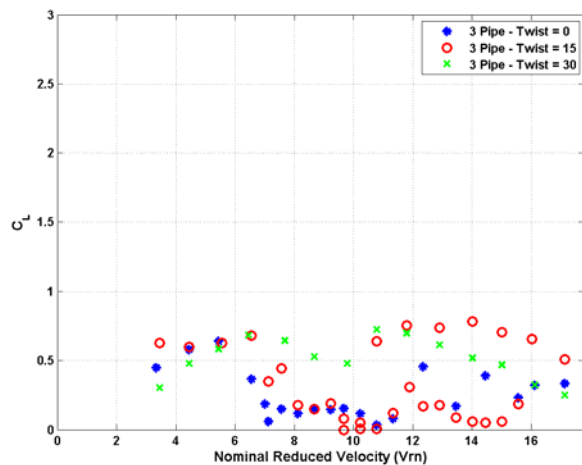


Figure 21. Mean lift coefficient of the riser system with 0, 15 and 30 degrees of twist, as a function of V_{rn} .

CONCLUSIONS

This model test was intended to provide guidance on the VIV behavior of a parallel grouping of three pipes, which were similar in configuration to a drilling riser with rather large kill and choke lines. The effect of kill and choke lines has been tested before and was known to influence VIV. It is expected that very small variations in relative diameters and gaps are important in the determination of VIV behavior. This test was for only one new geometry, but the results shown here are similar to other tests and may be useful in making inferences about similar systems in the future. The overall conclusions are:

1. The riser system exhibits significant VIV response at 0 and 90 degrees angle of attack and negligible VIV response at other angles of attack.
2. The addition of strakes prevents VIV of the riser system at all angles of attack over a wide range of reduced velocities.
3. The riser system exhibits lift coefficients with values of approximately 1 to 1.5 for angles of attack between 7.5 and 22.5 degrees, with the maximum at 15 degrees.
4. With strakes the riser system exhibits a maximum lift coefficient of 1.5 at approximately 45 degrees angle of attack.
5. The drag coefficient of the riser system increases substantially as the angle of attack increases.

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