

# PLUCK TESTS ON OPERATING DEEPWATER PIPELINE SPANS

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## ABSTRACT

Key uncertainties in the assessment of subsea pipeline spans for fatigue due to vortex-induced vibrations (VIV) are the effective axial force, the soil spring stiffness, and the soil damping. To reduce these uncertainties, pluck tests have been carried out, to determine the natural frequency and damping of single and multiple spans. These are carried out by pulling the span laterally at midspan with the ROV, until a 6mm or 8mm PP rope that serves as a weak link in the connection from the pipeline and the ROV breaks. The free vibrations resulting from this pluck are measured with accelerometers attached to the pipeline.

The paper presents selected results from these tests and their interpretation in terms modal frequencies and damping ratios. Already at the achieved amplitudes of vibration of up to about 0.01D, the results already show considerable nonlinearity and inelasticity that is thought to come from the soil supporting the pipe at the shoulders of the span, and can be captured in FE models by making the soil springs nonlinear and inelastic.

**Keywords:** pipeline, span, free span, VIV, vortex-induced vibrations, pluck test, natural frequency, damping ratio accelerometer, soil damping, soil stiffness

## INTRODUCTION

In pipeline spans VIV and the associated fatigue damage is normally avoided by limiting span length. This is especially so in high current where VIV could develop in relatively short spans with correspondingly high stress ranges. Therefore measuring VIV on a live span is difficult.

Pluck tests do not provide as much information, but they do provide two important parameters about which there would otherwise be considerable uncertainty: the natural frequencies of the span and corresponding modal damping ratios.

Especially for in-line VIV (i.e. horizontal vibrations), the damping has a strong effect on VIV amplitude [1], and in earlier span assessments fatigue damage was mostly dominated by in-line VIV.

For these reasons, a method of performing horizontal pluck tests was developed, and performed on a total of 12 spans. This paper describes the method and reports a selection of the results.

Before the pluck tests are performed, the pipeline is firstly instrumented by attaching one or more pipeline motion measurement units (PMMUs) on the free span. In a pluck test the pipeline is pulled horizontally from midspan with the ROV until a weak link in the connection between the pipeline and the ROV breaks, thereby releasing the pipeline. The resulting free vibrations are measured with one or two accelerometer units attached to the pipeline.

## PIPELINE MOTION MEASUREMENT UNIT (PMMU)

The PMMU for this project was developed at The University of Western Australia by modifying an Inertial Measurement Unit developed to track the motion of a free fall penetrometer [2]. This original device featured a set of triaxial MEMS accelerometers and gyros within a 77.5 mm diameter, 168.3 mm long steel cylinder. The unit was marinised for submerged operation and pressure tested to 6.2 MPa (620 m).

Other pipeline span monitoring systems have been reported previously, also using MEMS accelerometers. However, during planning of the present project it was identified that the expected pipeline motion required higher resolution and lower noise of acceleration measurement compared to conventional MEMS sensors. Therefore, the system was upgraded to 3-axis piezoelectric accelerometers, supplied by Bruel & Kjaer. These sensors have a measurement range of  $\pm 14g$  with a sensitivity of 500 mV/g. In lab trials the RMS noise from the MEMS device was 0.066 m/s<sup>2</sup> compared to only 0.005 m/s<sup>2</sup> from the piezoelectric device – a tenfold improvement.

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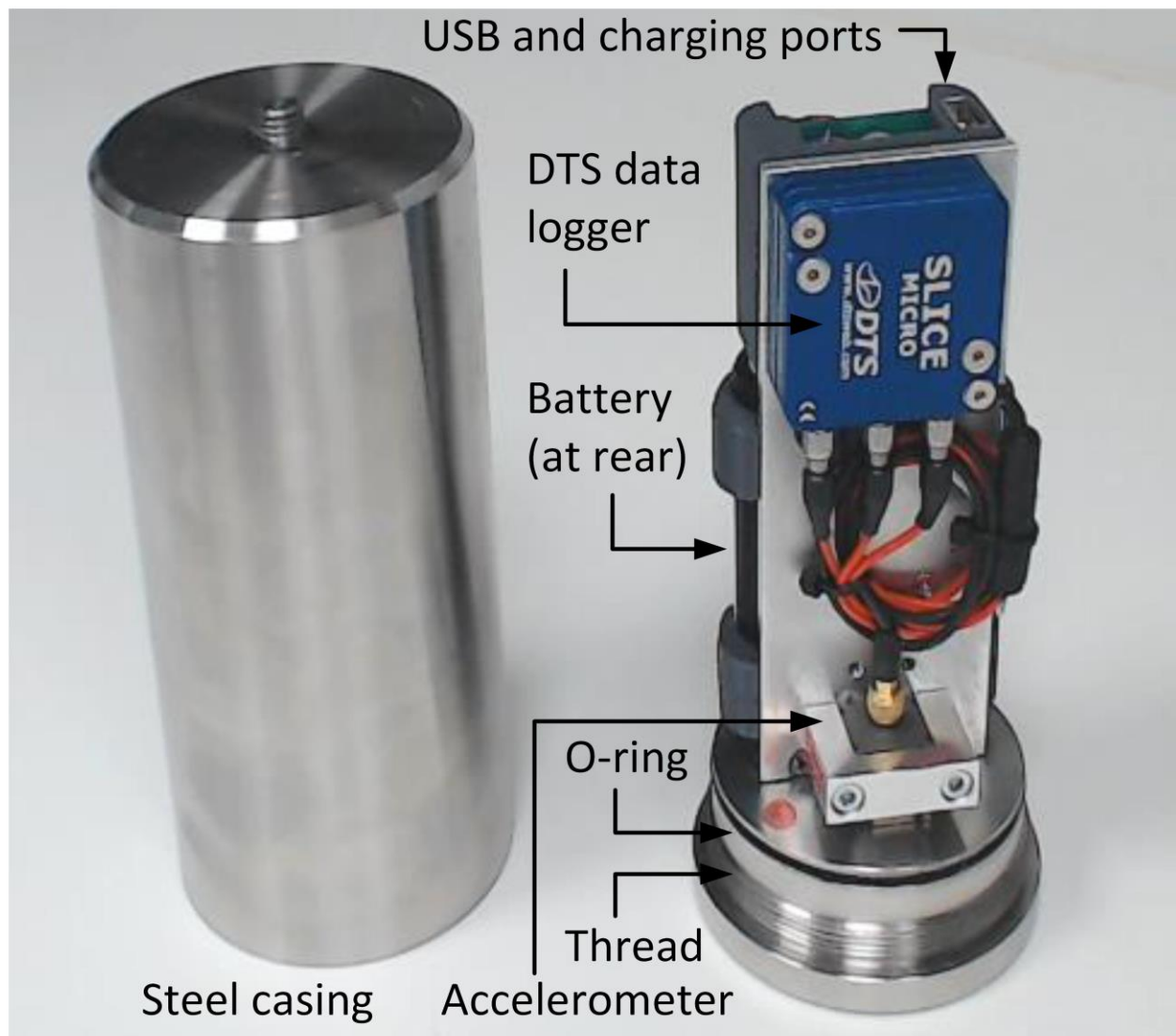
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The three accelerometer outputs are logged using a 16-bit DTS SLICE data acquisition system, equipped with 7 GB of flash memory. The accelerometers and the logging system are powered by twin 5200 mAh batteries. These allow 20 hours of operation between charges. The acquisition system runs continuously after the system is activated.

After each deployment and recovery of the device, the data is downloaded via a USB link using the DTS SLICEWare software and then chopped up into individual events at individual locations along the pipeline for subsequent interpretation. In this project, a data sampling rate of 500 Hz was used.

When deployed on the pipeline the acceleration signal was found to be three times noisier than in onshore trials. Initially it was thought that the ROV might be influencing this, but the proximity of the ROV had no influence on the noise. The noise had a standard deviation of around  $0.014\text{m/s}^2$  approximately uniformly distributed over the digitally resolved frequency band from 0 to 250Hz. It was concluded that this was most likely due to the turbulent flow of gas in the pipeline. It may be that the source of the noise was at higher frequency, and it could have been reduced by analog filtering prior to A/D conversion. Accelerometers on pipelines have been used previously to infer the internal flow rate, which supports this explanation [3][4].

One or two PMMUs were clamped on each span during the pluck tests, using clamps developed by DOF Subsea (Figure 2). Since there was no link between the two accelerometers, they were tapped together to synchronize their data streams prior to deployment. However, the accuracy of the clocks was not sufficient to maintain synchronization, so the time shift between one accelerometer and the other was estimated from the acceleration signature of the breaking of the weak links.



**Figure 1 Pipeline Motion Measurement Unit (PMMU) developed at The University of Western Australia**

### PLUCK TESTING METHODOLOGY

After the PMMU was attached to the pipeline, the weak link was set up. This consisted mostly of a 6mm PP rope, for which the capacity was measured onshore to be around 0.6 tons (6kN). The intent was not to snap the weak link suddenly as it becomes taught but pull gently increasing the ROV thrust until the PP rope breaks. In some cases, an 8mm PP rope was used instead, which was close to the limit of what the ROV could break in this manner.



Figure 2 Clamp develop by DOF with accelerometer clamped onto a partially strake-covered span

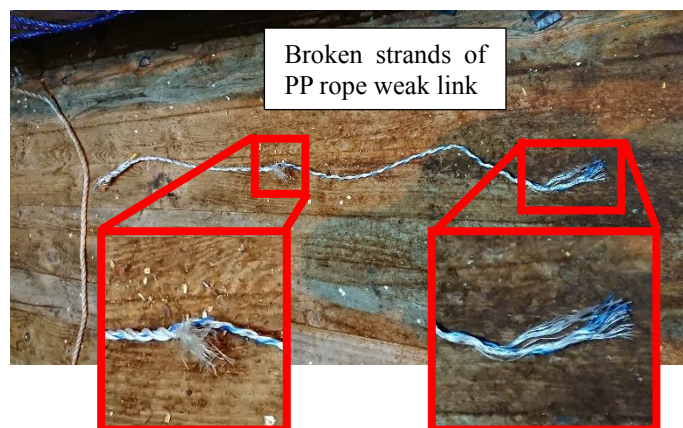


Figure 3 Broken PP rope weak link

Unfortunately, the PP rope tended to break by strands, rather than in one instantaneous, clean break. In Figure 3 the break in the PP rope is amplified in the right inset, but there is also damage to the rope amplified in the left inset. Possibly this represents strands breaking at different times over a period of around 0.2s, as suggested by accelerometer records such as Figure 5. This limited the amplitudes of vibration that could be achieved to about half the theoretically expected. The highest amplitude of vibration that was achieved was around 8mm. This refers to the amplitude of free vibration after the weak link was thought to be fully severed, and not to the maximum lateral displacement during pulling.

The acceleration data were not smoothed or integrated in time, but instead used directly as described in what follows.

## ACCELERATION DATA PROCESSING (ADP)

For this a computer program named ADP [5] was developed that calculates the free vibration response of a linear, viscously damped system with classical modes. It then determines the parameters of the system for which the calculated response best matches the recorded accelerations. For a single acceleration record, these parameters are the natural frequency, the damping ratio, and the initial amplitude and phase angle for each identified mode.

For several acceleration records, which could be different directions at the same accelerometer, or different accelerometers, the program can simultaneously fit all records, yielding the relative modal displacements at the accelerometer locations as well as the above parameters. It can also yield several components of the modal displacement, such as vertical and lateral, corresponding to the component acceleration records used.

To approximately capture nonlinear, inelastic response, time-dependent linearization is used. ADP can allow the natural frequency and damping ratio of any mode to change whenever the displacements for the mode are at zero. This is done by changing the modal stiffness and damping coefficient while conserving momentum and energy.

Thus, at most, the natural frequency and damping ratio can change every half period, giving rise to many more adjustable parameters to optimize the fit. However, based on some numerical experimentation, it was found better to allow the parameters to change only after every full period or several periods. One can then plot the natural frequencies and damping ratios as a function of the amplitude of vibration, as in Figure 7, to get an indication of nonlinear and inelastic behavior. For such plots, the amplitude plotted is that of the first peak or through during the period in which the dynamic properties remain constant.

The term “nonlinear mode” is used here to mean an ADP fit for time-dependent properties for the mode in question, used to approximately represent nonlinearity as described above.

ADP has been extensively validated in [5], using artificial acceleration records, including ones generated by finite element analysis. The validation exercise shows that it works well for the single-mode linear as well as nonlinear case, and for the multi-mode linear case. For multi-mode, nonlinear response, the nonlinearity typically introduces coupling between the modes, and although ADP can handle such cases, the ADP model to fit the response does not include the coupling between the modes. The result is that with two nonlinear modes, the fit may not be much better than with one. An exception is made when one mode is horizontal and the other vertical. For this case fitting both simultaneously as nonlinear modes has worked, perhaps because the nonlinear interactions between the vertical and lateral modes at the amplitudes of the tests is weak.

## EFFECT OF CURRENTS DURING TEST

Since currents can affect the dynamic behavior of the spans, the current speed during the test was measured at the ROV's TMS (Tether Management System) about 20m above the seabed. This was converted to a current speed at the pipeline elevation by assuming the current velocity is proportional to the distance above the seabed to the power of 1/7. Further it is assumed that the current was assumed to be normal to the pipeline, constant along the length of the span, that Morrison's equation applies, and that the velocity associated with pipe motion is small compared to the current velocity, so that Morrison's equation may be linearized. On this basis it is found that the contribution from hydrodynamic damping to the Scruton damping parameter can be written as

$$K_{Sh} = \pi^2 (m_{ratio} + C_{as}) \zeta_h = C_d U_R$$

where  $K_{Sh}$  is the contribution from hydrodynamic damping to the Scruton mass-damping parameter,  $\zeta_h$  is the hydrodynamic contribution to the modal damping;  $m_{ratio}$  is the total mass of the pipe divided by the mass of water it displaces;  $C_{as}$  is the added mass coefficient in still water (accounting for seabed proximity effect as in [1], but not considering the effect of the flow velocity on the in line added mass);  $C_d = 1$  is the drag coefficient used in Morrison's equation (from Appendix E of [6]); and  $U_R$  is the reduced velocity, i.e. the current velocity normal to the pipe at the pipe elevation expressed in pipe diameters (including coating) per natural period of oscillation in still water.

The values of hydrodynamic damping obtained by the above method give only a very rough indication of the effect of currents on the test results. For more accurate results one would need to measure currents closer to the seabed and measure the direction as well.

The method to calculate damping is from [6], though there appears to be a slight inconsistency in the result of [6], which is corrected in the result given above. Other formulations for damping are available. Those from [7] are often used for risers involving mostly cross-flow response [8], but not here.

## SYNCHRONIZATION OF ACCELEROMETERS

When the records from two accelerometers are used simultaneously, their synchronization is based on the acceleration signature of what appears to be the breaking of the PP rope. This is shown in Figure 5. Therein the time values have been shifted so that  $t=0$  corresponds to the initiation of the breaking process for the weak link. The same is done for both accelerometers, and it is assumed that the shifted times thus obtained are consistent. It is the time from initiation of the breaking process of the weak link.

## SPAN 1

The seabed and pipeline profiles for Span 1 are shown in Figure 4. Therein the seabed profiles shown are from sonar equipment installed on the ROV that measures the seabed elevation approximately 1 to 2m to to each side the the pipeline centre line. Due to scour, the seabed directly under the pipe is typically a bit lower. It is for this reason that the span extends to the vertical dashed green lines, rather than only to where the seabed profile intersects the bottom of the pipe. This extent of the span is estimated from the video cameras on the ROV rather than the sonar elevation measurements, giving a span length of 40m from the visual inspection immediately prior to testing. (Scour can also change the seabed profiles, and, whereas the span length is from the visual inspection immediately prior to testing, the seabed profiles are from a few months earlier.)

The gap under the pipeline at midspan is more than the pipe diameter. Therefore a still-water added mass coefficient of  $C_{as} = 1$  is used with no increase on account of seabed proximity.

Soil samples are not available for the exact location of the span. The descriptions of the nearest samples are shown below:

Vibrocore 52, 1.7km from Span 1:

| Depth<br>(m) | Summary of Layer<br>Description                                                  | Water<br>Content<br>% | Bulk<br>Density<br>(Mg/m3) | Dry<br>Density<br>(Mg/m3) |
|--------------|----------------------------------------------------------------------------------|-----------------------|----------------------------|---------------------------|
| 0            | Light olive grey fine to coarse SAND with much shell fragments and shell debris. |                       |                            |                           |
| 0.10         |                                                                                  | 35                    |                            |                           |
| 0.30         | SHELLS and CORAL fragments.                                                      |                       |                            |                           |
| 0.32         |                                                                                  | 42                    |                            |                           |
| 0.34         | End of Borehole                                                                  |                       |                            |                           |

Remark: Core barrel bent - retest VC52A

Vibrocore 52a, Nominally at same location as 52:

| Depth<br>(m) | Summary of Layer<br>Description                                                                                                | Water<br>Content<br>% | Bulk<br>Density<br>(Mg/m3) | Dry<br>Density<br>(Mg/m3) |
|--------------|--------------------------------------------------------------------------------------------------------------------------------|-----------------------|----------------------------|---------------------------|
| 0            | Light olive grey slightly cemented slightly silty fine to coarse SAND with much shells and shell fragments.                    |                       |                            |                           |
| 0.10         |                                                                                                                                | 26                    |                            |                           |
| 0.30         |                                                                                                                                | 26                    |                            |                           |
| 0.50         |                                                                                                                                | 28                    |                            |                           |
| 0.60         | Light olive green silty fine to medium SAND with much shells and shell fragments.                                              |                       |                            |                           |
| 0.70         |                                                                                                                                | 33                    | 1.87                       | 1.41                      |
| 0.90         | Dark grey slightly sandy clayey SILT with some shell debris and large pockets of light olive green fine to medium shelly sand. | 34                    | 1.92                       | 1.44                      |
| 1.10         |                                                                                                                                | 36                    | 1.90                       | 1.40                      |
| 1.30         |                                                                                                                                | 33                    | 1.93                       | 1.46                      |

Vibrocore 54, 1.4km from Span 1:

| Depth<br>(m) | Summary of Layer<br>Description                                                                   | Water<br>Content<br>% | Bulk<br>Density<br>(Mg/m3) | Dry<br>Density<br>(Mg/m3) |
|--------------|---------------------------------------------------------------------------------------------------|-----------------------|----------------------------|---------------------------|
| 0            | Pale olive to light olive green medium to coarse SAND with much shell fragments and shell debris. |                       |                            |                           |
| 0.10         |                                                                                                   | 21                    |                            |                           |
| 0.20         | Dark olive grey fine sandy SILT with occasional shell fragments and shell debris.                 |                       |                            |                           |
| 0.30         |                                                                                                   | 28                    | 1.92                       | 1.50                      |
| 0.50         |                                                                                                   | 29                    | 1.91                       | 1.49                      |
| 0.70         |                                                                                                   | 29                    | 1.93                       | 1.50                      |
| 0.90         |                                                                                                   | 29                    | 1.98                       | 1.53                      |
| 1.10         | End of Borehole                                                                                   |                       |                            |                           |

The pipe properties for Span 1 are:

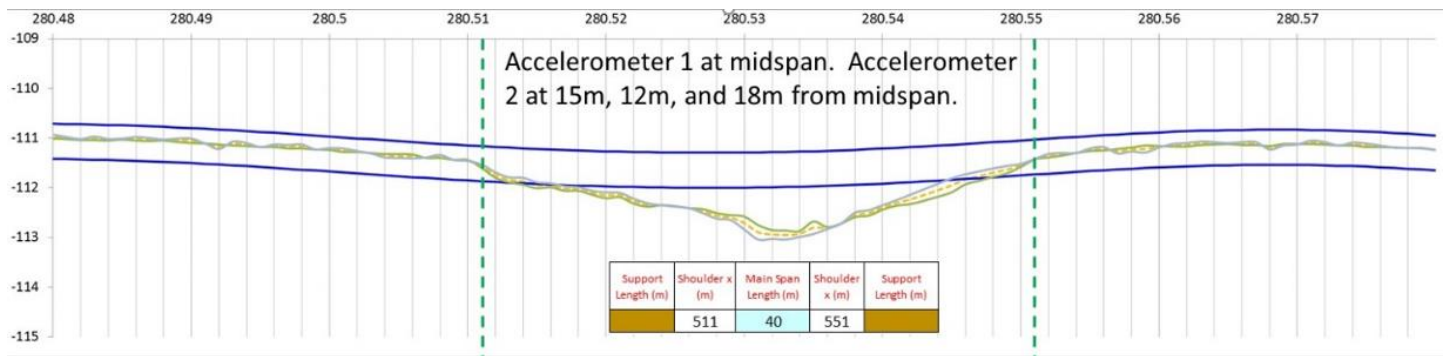
|                                   |                             |
|-----------------------------------|-----------------------------|
| Outer Diameter including coatings | $D = 705.6 \text{ mm}$      |
| Mass Ratio                        | $m_{\text{ratio}} = 1.30$   |
| Estimated Flexural Rigidity       | $EI = 381.23 \text{ MNm}^2$ |

The estimated flexural rigidity includes an allowance for the concrete weight coating calculated according to the method in [1] which approximately accounts for cracking as well as limited bond strength between the steel pipe and the concrete coating.

There is significant uncertainty about the effective axial force  $N$  when tested. Only the minimum lay tension required as a function of pipelay conditions are available and not the actual lay tension recorded during installation. By looking at vertical profiles with the SpanFit method [9], an effective axial force of  $N = -1.3\text{MN}$  (negative for compression) has been estimated, and used as a base case also for other spans unless otherwise noted. (The temperature is close to ambient, and the increase in axial compression under fully constrained conditions due to an operating pressure of 154 bar would be 1.6MN.)

The lateral soil spring stiffness is estimated to be  $k_L = 12.22 \text{ MPa}$  from the formulation for “loose sand” in Section 7.2.4 of [10] (F114 “loose sand”). Throughout this paper “F114” refers to Sections 7.2.2 and 7.2.4 of [10].

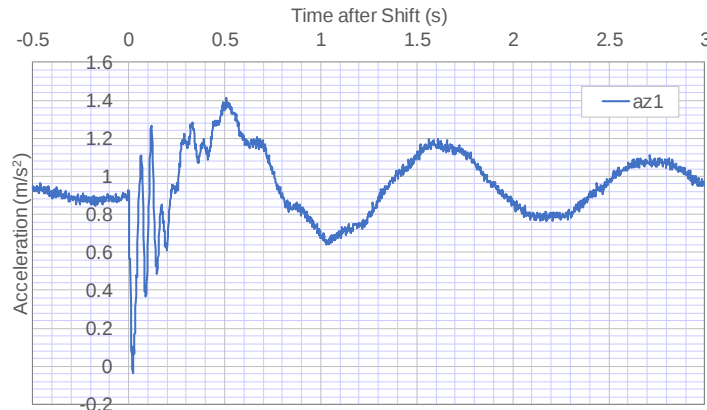
With the above properties, in-line natural frequencies of 0.95 and 5.37 Hz are calculated, for the first and third mode respectively, using the in-line analytical solution in [11],[12]. (The 2<sup>nd</sup> mode is antisymmetric and not expected to be excited by pulling and releasing at midspan.)



**Figure 4 Profiles for Span 1**

Several pull and release tests were performed on this span with one accelerometer always near midspan (the accelerometer could not be clamped onto the exact same for location from which the span was pulled), and the other accelerometer at different distances from midspan. Each of the tests is referred to as an “event”. For instance Event 01\_16 is event number 16 on Span 1. (Not all Events are pull-and-release tests, however.)

Event 01\_16 is the one for which the highest amplitude of vibration of 8mm (0.011D) was achieved. The lateral acceleration at midspan for the first 3s is shown in Figure 5. The initial acceleration spikes may be strands of the PP rope breaking sequentially, but after 0.83s it looks fairly certain that the rope is fully severed and free vibrations are being measured. Therefore ADP fitting for this event is performed in the range  $t \in [0.83s, 15s]$ .

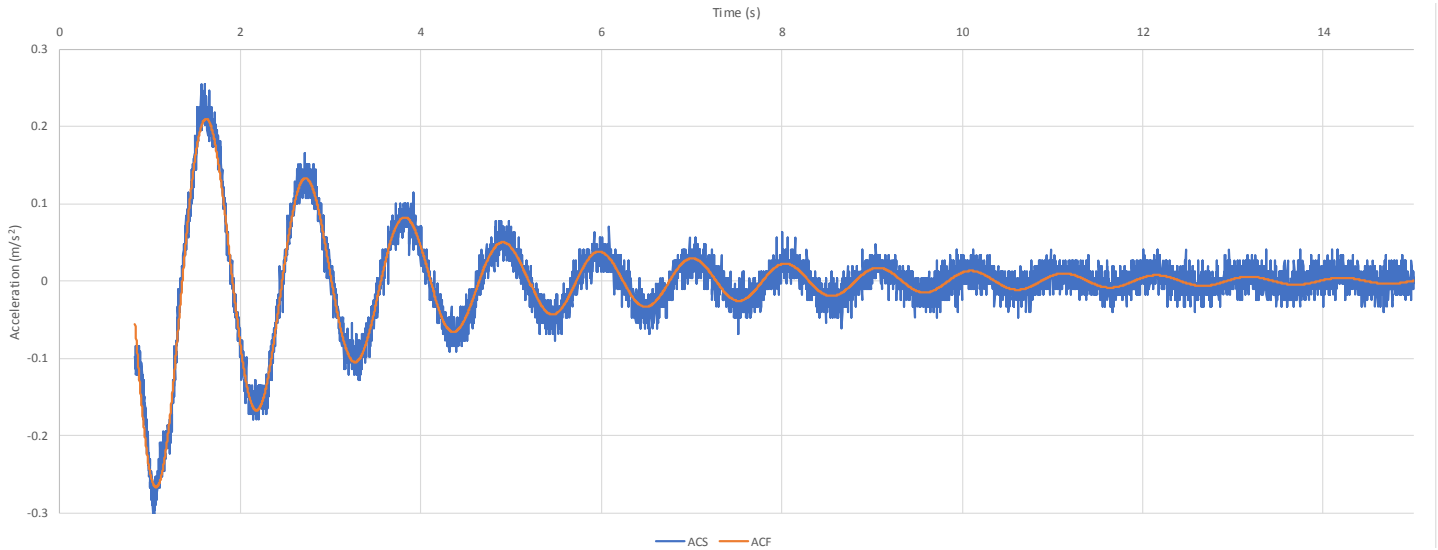


**Figure 5 Lateral acceleration at midspan for Event 01\_16.**

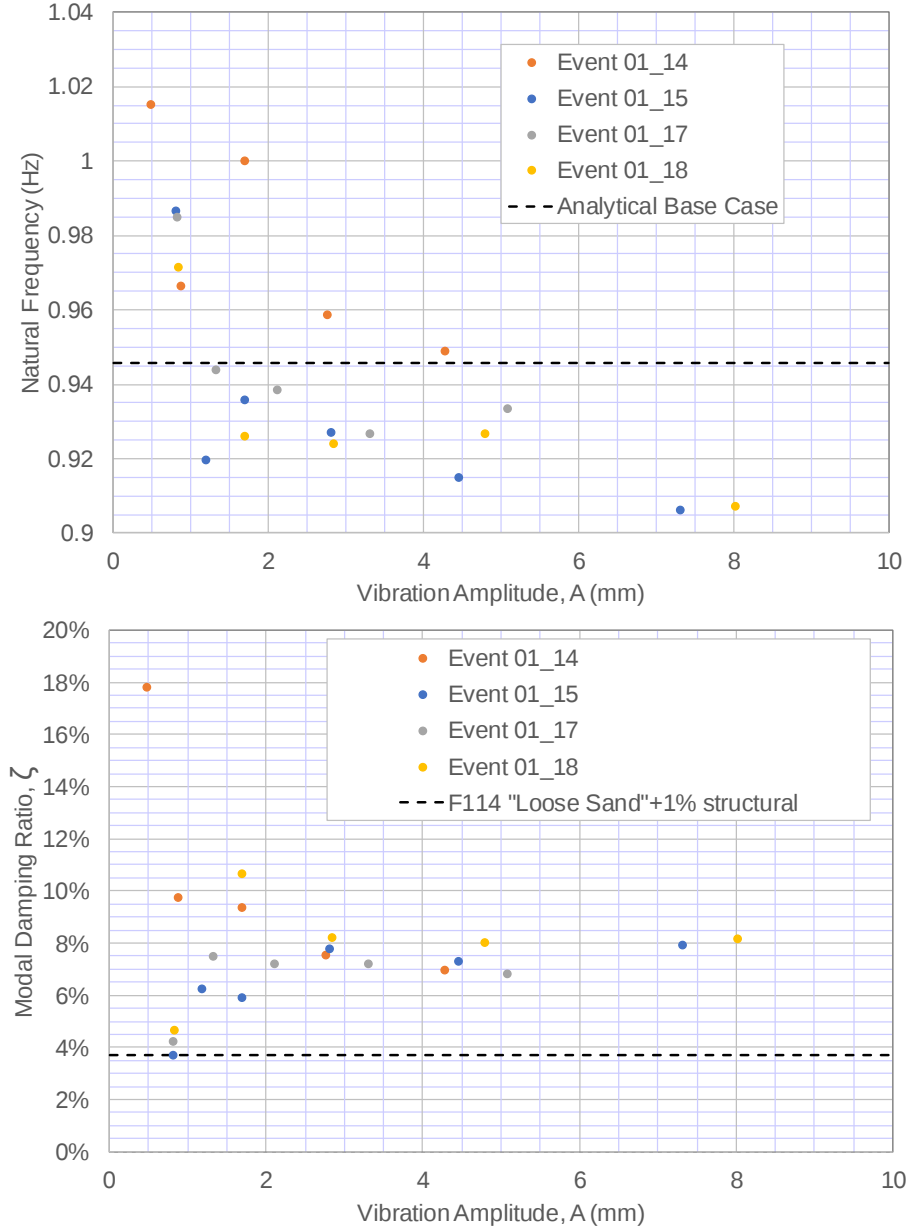
ADP was used with a sequence of runs with increasing sophistication of the fitting, each time using the previous run for the initial guesses of the optimal fit parameters that were then further optimized by ADP. (ADP finds a local minimum, not necessarily the global minimum.) For Event 01\_16, this culminated in a 2-mode fit (mode 1 horizontal and mode 1 vertical), with simultaneous fitting of 4 acceleration records (vertical and lateral for each of the two accelerometers). For the dynamic properties for both modes are allowed to update at every full period (when the displacement is zero), for the first 5 periods. For the 6<sup>th</sup> and subsequent periods the same dynamic properties as for the 5<sup>th</sup> are used. These dynamic properties (natural frequency and damping ratio) are adjusted to minimize the sum of the squares of the acceleration errors over all 4 records. The resulting fit for the lateral acceleration at midspan is shown in Figure 6.

Performing such ADP fits for a number of the pull-and-release “events” on this span and plotting the optimum-fit natural frequencies and damping ratios for each full period as a function of the displacement amplitude at the first half cycle of each period yields Figure 7. This shows that the natural frequencies increase as the amplitude of vibration decays. The maximum amplitude of 8mm corresponds to 0.011 D, whereas in-line VIV can produce amplitudes up to 0.18 D, and cross flow up to 1.3 D according to [1].

The natural frequencies in Figure 7 span the analytical value of 0.95Hz. At a vibration amplitude of 2 to 3mm the test data are closest to the analytical. For VIV assessments the most relevant natural frequency is the one at the largest test amplitude, since VIV amplitudes could be still larger. This gives a reference frequency of 0.91 Hz from Figure 7. Exact agreement between this measured reference frequency and the analytical one can be achieved by any one of the following adjustments to the input to the analytical model: increasing the span length from  $L=40\text{m}$  to  $L=40.8\text{m}$ , increasing the axial compression from  $N= -1.3\text{MN}$  to  $N= -1.73\text{MN}$ , decreasing the effective lateral soil spring stiffness from  $k_L = 12.22\text{MPa}$  to  $k_L = 7.86\text{MPa}$ .



**Figure 6 ADP fit for lateral acceleration at midspan for Event 01\_16**



**Figure 7 ADP [5] optimum-fit natural frequencies and damping ratios mode 1 in-line response of Span 1**

Any of these changes is well within the range of uncertainty of the input parameter, so there is no surprise about the level of natural frequencies, but what is remarkable is that even at such low amplitudes there are already significant indications of nonlinearity. This is most likely soil nonlinearity, as modeled in [13] by allowing amplitude-dependent effective soil spring stiffnesses to approximately capture the nonlinearity.

The damping in Figure 7 is consistently at  $\zeta=8\%$  for amplitudes above 2mm. This corresponds to a Scruton mass-damping parameter of  $K_S=1.8$ . According to the in-line VIV response function in [1] (with the safety factors set to 1), this is enough to fully suppress pure in-line VIV.

At low amplitudes, the acceleration signal is smaller than the noise, so it is not surprising that the scatter in damping values increases. Considering that Figure 7 represents several pull and release events, the results look consistent.

For comparison, the dashed line shows the soil damping for F114 “loose” sand (i.e. according to Section 7.2.2 of [10]) plus 1% estimated structural damping. (F105 [1] estimates a range of 1% to 2% for structural damping with concrete coated pipes, in part due to energy dissipated at the bond between the concrete and the steel, but for the very low amplitudes of the test, the effective value is judged more likely to be at the low end or below the F105 range.)

The damping ratios in Figure 7 include any hydrodynamic damping. Based on the current measurements, the reduced velocities  $U_R$  ranged from 0.09 to 0.31 resulting in calculated hydrodynamic damping ratios  $\zeta_h$  ranging from 0.4% to 1.4%, so perhaps the soil plus structural damping is 7% instead of 8%. Subtracting also the 1% for structural damping leaves 6% attributed to soil damping.

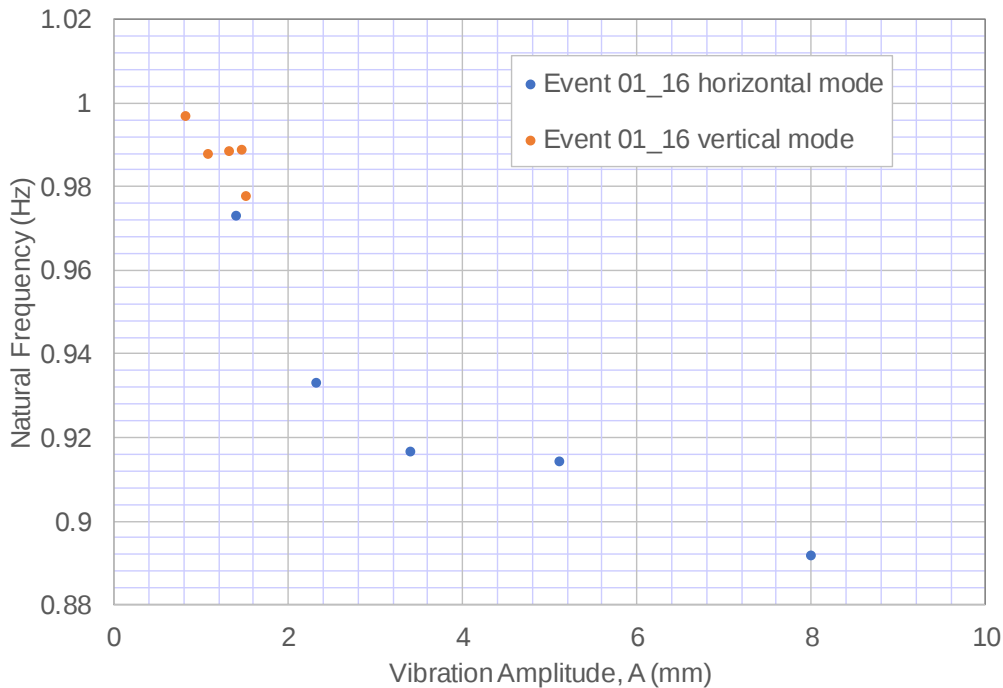
Due to increasing nonlinearity and inelasticity with increasing amplitude, one might expect the damping ratio to start low and increase with increasing amplitudes, and it does this for other spans (see Figure 11 and Figure 12), but apparently not for this one. Not only linear viscous damping but also hysteretic damping due to inelasticity can result in amplitude-independent effective damping. E.g. inelasticity according to Masing's rule ([14],[13]) and a power-law backbone curve will do this. Still it is not clear why there is no evidence of a drop in damping at lower amplitudes for this span.

Unintentionally the pull-and-release test also introduced vertical motions that were picked up by the accelerometers and included as a 2<sup>nd</sup> mode in the ADP processing. For Event 01\_16, this yields the vertical frequencies compared in Figure 8 with the horizontal frequencies. The vertical frequencies are a bit higher, but that appears to be mostly because of the lower amplitudes of the vertical vibrations. I.e. for the same amplitude of vibration, the vertical and horizontal frequencies are very close.

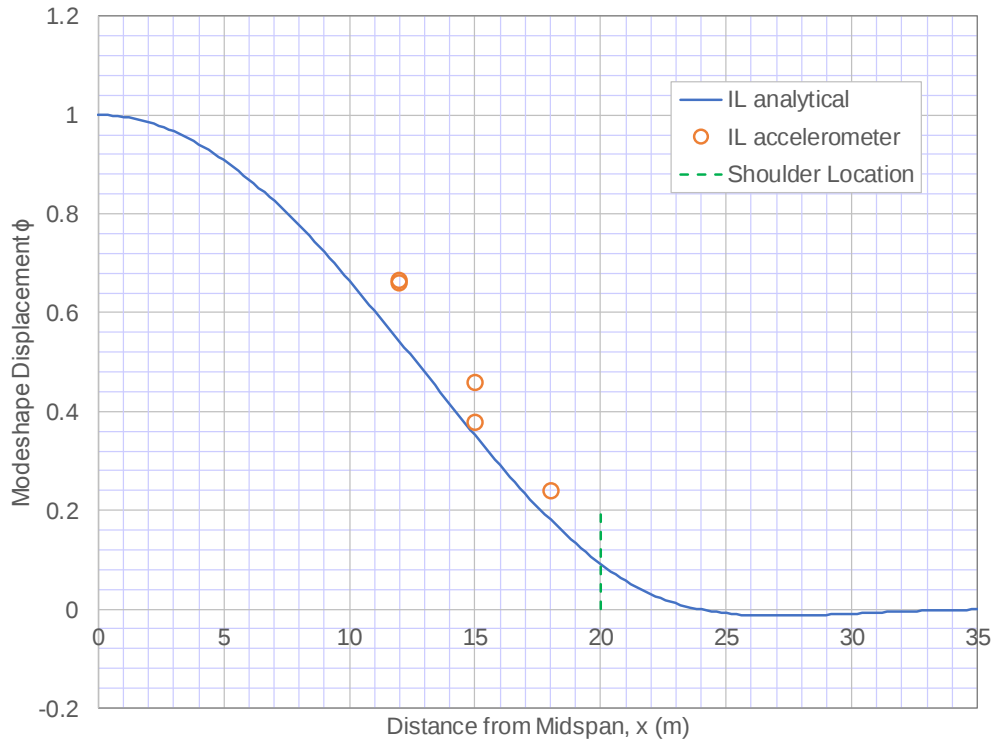
The 2-mode, 4-records ADP processing also yields mode shape information. The horizontal mode turns out to be not purely horizontal and the vertical no purely vertical. Specifically, the optimum-fit direction of motion for the horizontal mode at midspan is about 10° from horizontal and the vertical mode is at about 1° from vertical. I.e. they are neither fully aligned with the axes nor orthogonal. Further, these optimal fit directions are not consistent from event to event nor from one accelerometer to the other. This is not surprising since the vertical and horizontal natural frequencies are so close, especially at the same amplitudes. (Mode shapes with distinct natural frequencies should be orthogonal, but if the natural frequencies coalesce, any linear combination of the two modes is also a mode.)

Further mode shape information comes from the 2<sup>nd</sup> accelerometer that was clamped onto the pipe at different distances from midspan for different events. This is compared in Figure 9 to the analytical mode shape. The agreement is as good as it can be expected to be given survey inaccuracies in determining the exact positions of the accelerometers and the exact locations of the touch-down points.

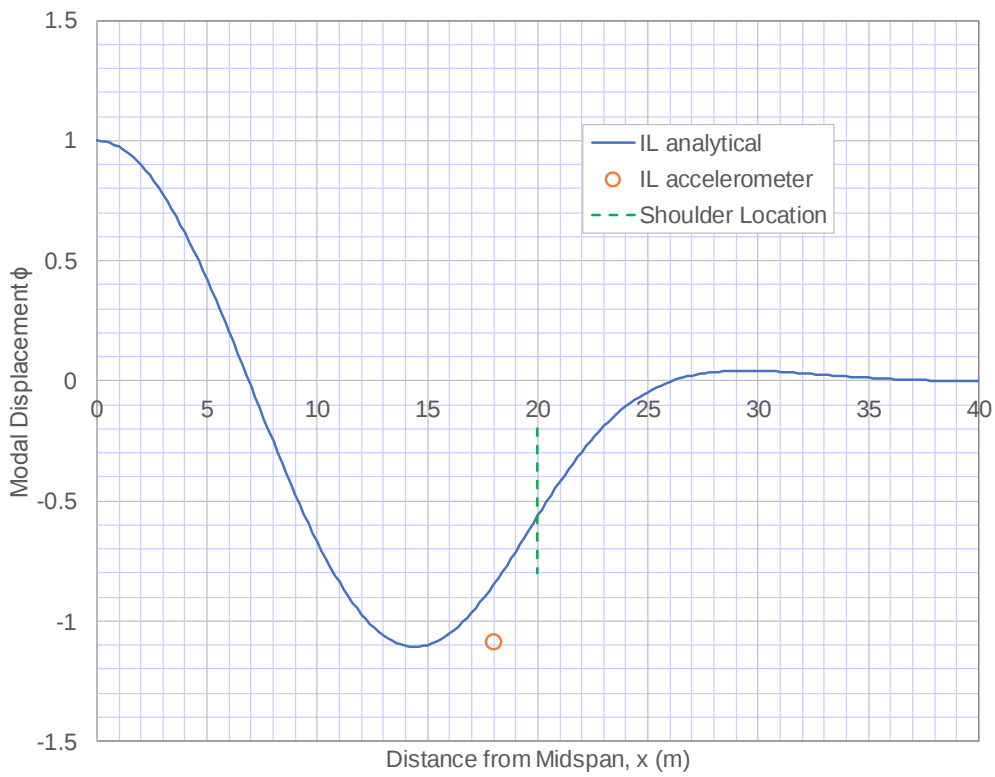
[Survey positions of the vessel are by DGPS and from the vessel to the ROV by sonar transponder. The combined anticipated maximum position error for deepest span considered is  $\pm 1.5\text{m}$ . In theory this means that the relative positions like the span length could have as much as double the error, but the quality of the results suggests that better accuracy was achieved in the relative positions.]



**Figure 8 Natural frequencies of vertical and horizontal modes for Event 01\_16 (Span 1)**



**Figure 9 Span 1 horizontal modeshape from ADP processing compared with analytical mode shape**



**Figure 10 Span 1 horizontal mode 3 (based on Event 01\_18)**

Similar results for the 3<sup>rd</sup> horizontal mode are shown in Figure 10. The 3<sup>rd</sup> mode was identified for Event 01\_18 only, with a natural frequency of 4.9 Hz obtained by ADP processing. This compares well to the analytical frequency of 5.37Hz. To bring about exact agreement between the analytical and measured 3<sup>rd</sup> mode frequency the soil spring stiffness would need to be changed from  $k_L = 12.22\text{MPa}$  to  $k_L = 5.17\text{MPa}$ . This is not too far from the  $k_L = 7.86\text{MPa}$  that matches the 1<sup>st</sup> mode frequencies at the highest recorded amplitudes. Unfortunately, the polarity of the lateral acceleration from the 2<sup>nd</sup> accelerometer relative to the 1<sup>st</sup> was not documented and depends on how the accelerometer was clamped onto the pipe. Therefore, the mode shape results are plotted with the polarity that results in much better agreement with the analytical result.

## OTHER SOIL-TO-SOIL SINGLE SPANS

The test program included two other single spans with soil (rather than rock dump) at both shoulders:

- Span 12 has a length of  $L=29\text{m}$ . It is within 0.5km of Span 1 with similar soil properties expected and the same pipe properties. The natural frequencies and damping ratios for the 1<sup>st</sup> horizontal mode from ADP processing are in Figure 11. The corresponding analytical base case analytical horizontal natural frequency of 1.68Hz, as indicated by the dashed line.
- Span 8 with  $L=28\text{m}$  is in deeper water also mainly in sands, but they tend to be finer and more silty, though coarse sands and even thin layers of natural gravels (possibly transported by turbidity currents) are also found in the area of Span 8. The nominal pipe wall thickness at Span 8 is 17.1mm (as compared to 18.9mm for Spans 1 and 12), but the ID, coatings and estimated gas density are the same for all spans. This gives Span 8 an analytical base case natural frequency of 1.73Hz, again assuming F114 “loose sand”. The natural frequencies and damping ratios from ADP processing are shown in Figure 12.

The natural frequency results for all single, soil-to-soil spans are remarkably consistent. In all cases the experimental results for different amplitudes span the analytical result based on F114 “loose sand”, with essentially exact agreement at very low amplitudes, of 2 to 3mm for Span 1, and about 0.8mm for Spans 8 and 12.

The damping ratios for Spans 8 and 12 match the estimated damping for F114 “loose sand” plus 1% structural damping at about the same amplitudes for which the natural frequency matches. However, for Span 1, the drop in damping ratio at low amplitudes does not seem to occur, or at least it has not been established from the acceleration records.

## MULTI SPANS OVER ROCK SUPPORTS

Span 6, a multi-span, is shown in Figure 14. The numbers in blue background are the span lengths, those in grey are lengths supported by rock dump, and those in white are local axial coordinates  $x$  of the shoulders, all in meters. The brown zone to the right indicates native soil at the right shoulder of the right span.

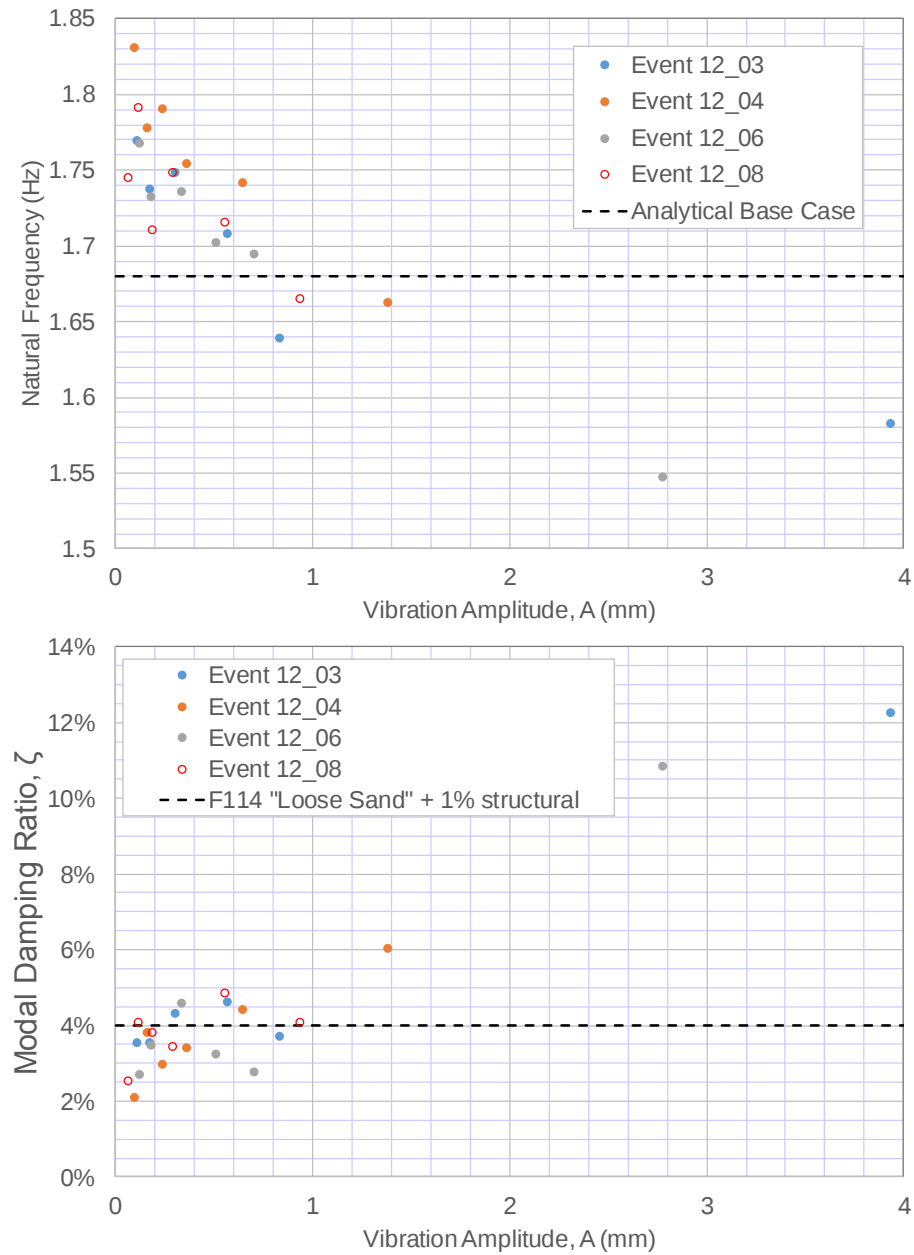
The pull is always at midspan of the right span. One of the accelerometers was always near the pull location, and the other is in the middle or left span, or absent.

Steel wall thickness here is 18.4mm, and other properties are as for the other spans. This results in  $m_{\text{ratio}} = 1.28$ ,  $D = 704.6\text{mm}$ , and  $EI = 371.25\text{MNm}^2$ .

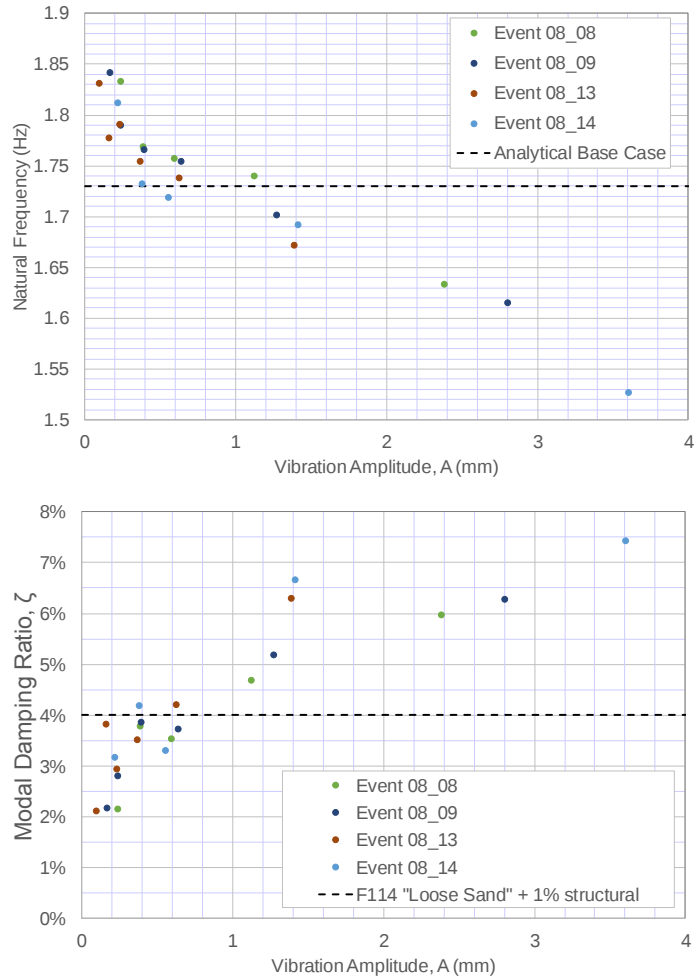
If the right span were a single span with F114 “loose sand” at both shoulders, the base case analytical natural frequency would be 1.77Hz. Similarly for the 32m-long left span on its own with F114 “dense sand” at both shoulders (as an approximation for rock), the analytical natural frequency is 1.50Hz. Due to interactions between the spans, a frequency below 1.77Hz and another below 1.50Hz are expected, as well as other modes.

ADP processing of the accelerometer records does indeed produce such frequencies (Table 1). A total of 5 linear modes are used to fit lateral midspan acceleration record for Event 06\_07 resulting in the fit of Figure 13. [Nonlinear and multi-mode fitting is a bridge too far for ADP, not because the optimization algorithm cannot handle it (though that is challenging too) but because the classical modes assumption underlying ADP appears to break down. Then adding more fitting parameters degenerates into a curve fitting exercise, rather than a system identification exercise, providing additional insight in to the physics of the system.]

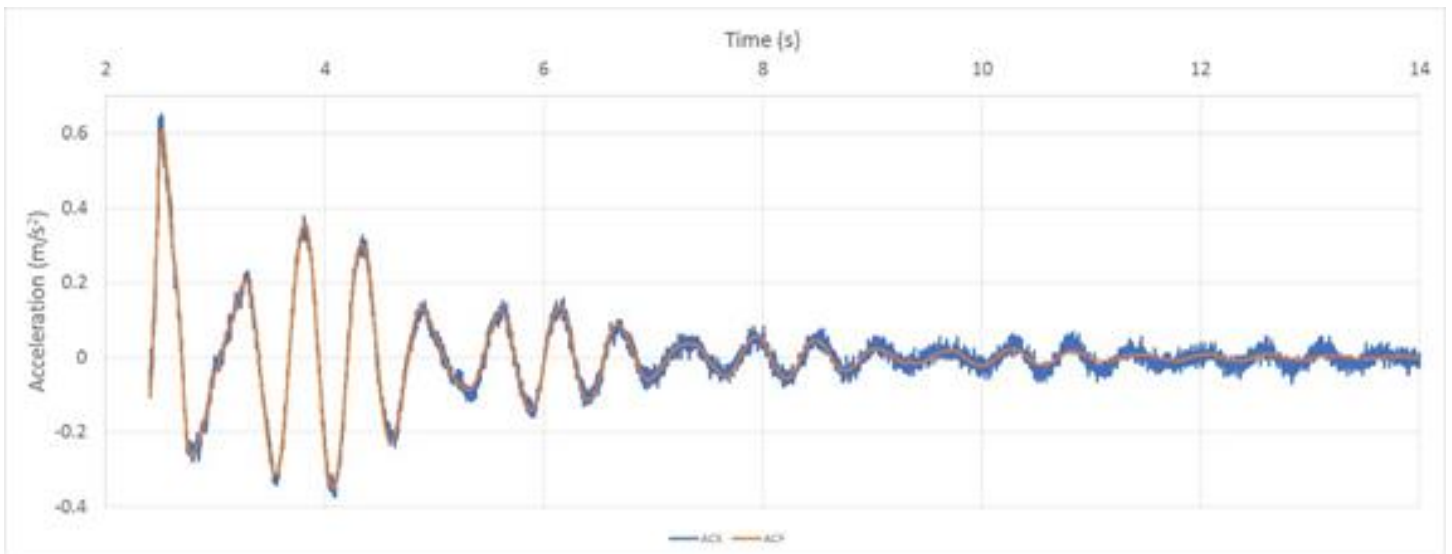
The first 3 modes can consistently be identified across 7 events processed with ADP, with results shown in Table 1. So far no serious effort has been made to relate these modes to an analytical model, but it seems likely the Mode 1 involves mainly motion of the left, 32-m long span, and Modes 2 & 3 involve mainly motion of the middle and right spans, with opposite phase for Mode 2, and in-phase for Mode 3. Part of the challenge in modelling this multi-span is that there are additional adjacent spans (not included in Figure 14) that could affect the behavior. These are covered in earlier surveys but not in the pre-test survey and could have been altered by scour.



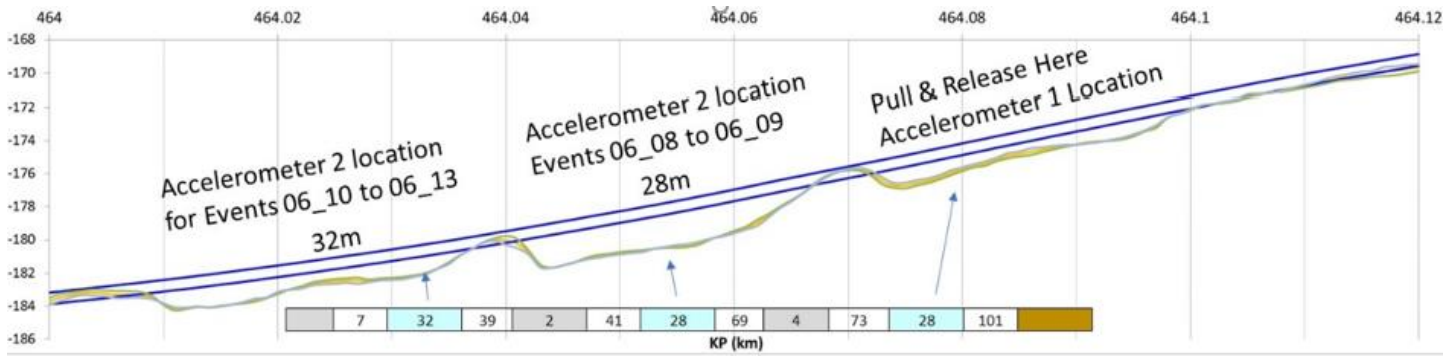
**Figure 11 Natural frequencies and total modal damping ratios from ADP processing for Span 12**



**Figure 12 Natural frequencies and modal damping ratios  $\zeta$  from ADP processing for Span 8**



**Figure 13 Event 06\_07 (Span 6) showing lateral acceleration for the right span of Figure 14; ADP fit with 5 linear modes using a single acceleration record**



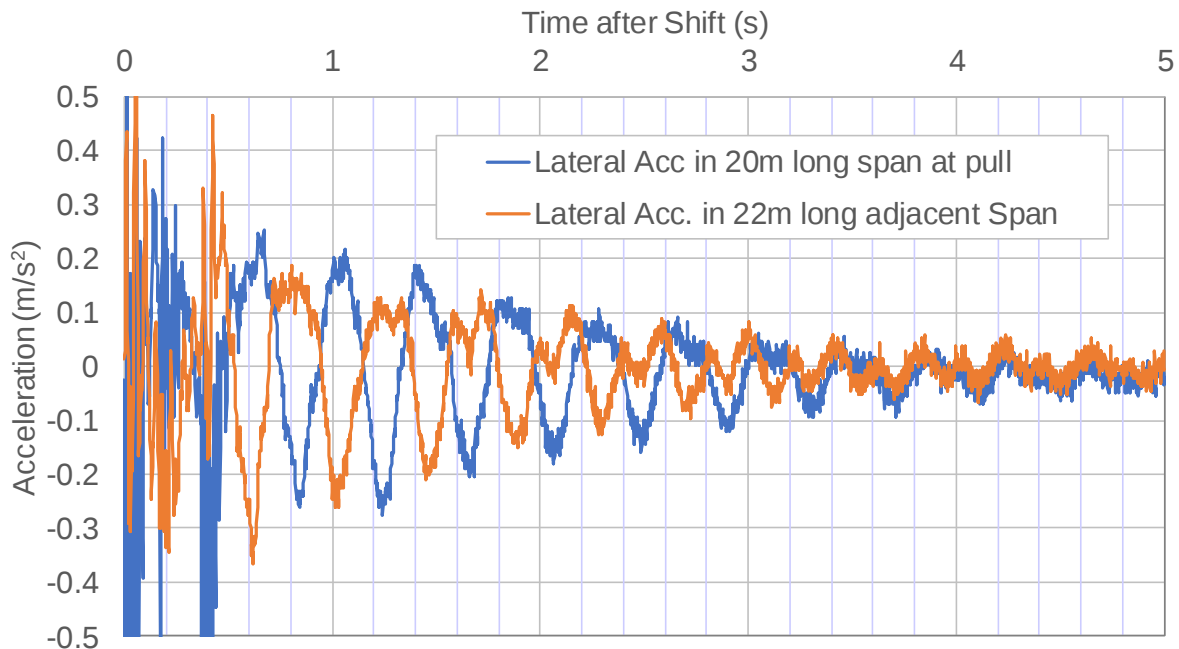
**Figure 14 Vertical profile for Span 6**

| Mode                                            | 1    | 2    | 3    |
|-------------------------------------------------|------|------|------|
| Average natural frequency from 7 Events (Hz)    | 1.34 | 1.72 | 2.18 |
| Average average total damping ratio             | 4.1% | 3.4% | 3.4% |
| Average soil + structural damping ratio         | 2.7% | 2.3% | 2.6% |
| Maximum modal amplitude achieved (mm)           | 1.10 | 3.77 | 1.42 |
| Coefficient of Variation (CoV) of natural freq. | 1.8% | 1.0% | 0.4% |
| CoV of total damping ratios (across events)     | 28%  | 13%  | 21%  |
| CoV of soil and structural damping ratios       | 59%  | 29%  | 28%  |

**Table 1 ADP fitting results for Span 6**

The damping ratios for this multi-span on rock are much lower than for the single spans on soil. To some extent this may be because of the lower amplitudes achieved for the multi span, but it also seems reasonable that the damping for rock should be lower than for soil. Other multi spans yielded similar low damping values, except one very long span with a flimsy intermediate soil support, where the damping was so high that hardly any vibrations could be measured.

There was also one multi-span, Span 16, for which ADP failed to produce a good fit even though various options were tried including a single nonlinear mode and multiple linear modes. The lateral acceleration records are shown in Figure 15. The pull was on a 20m-long span, and the 2<sup>nd</sup> accelerometer on an adjacent 22m long span, separated by 5m of rock dump support. However, the other sides of the accelerometer-bearing spans had grout-bag supports. It is conceivable that this configuration lead to response that is nonlinear and multi-mode with modal interactions and therefore could not be satisfactorily captured with ADP.



**Figure 15 Lateral acceleration records for Event 16\_15 (Span 16)**

## CONCLUSIONS

Analyses in [13] show a strong effect of nonlinear and inelastic soil behavior on the dynamic properties (i.e. the natural frequency and damping ratio) of pipeline spans. These field tests support that conclusion for single spans with native soil (probably sand or silty sand) at the shoulders.

For these spans, recommendations for soil stiffness and damping in Sections 7.2.4 and 7.2.2 of [10] seem to apply for only extremely low amplitudes. Even at the still low vibration amplitudes up to about 0.01 D achieved in these tests, the effective soil stiffness already appears to be considerably lower, and the effective soil damping higher. This has strong implications for span assessments, especially for in-line VIV which is much more sensitive to damping.

For multi spans involving rock dump, the damping is found to be much lower. The response in such cases may be both nonlinear and multi-mode, which makes it difficult to interpret.

Further efforts are needed to compare the accelerometer data for multi spans to predictions with models that include nonlinear and inelastic soil supports.

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