FULL SCALE VIV RESPONSE MEASUREMENTS OF A DRILL PIPE IN GULF OF MEXICO LOOP CURRENTS

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ABSTRACT

In September 2004 BP retrieved a Gulf of Mexico drilling riser due to excessive loop currents. Whilst waiting for the currents to diminish an impromptu full scale riser Vortex Induced Vibrations (VIV) test was carried out using the drilling riser standalone monitoring system. A 6-5/8 inch drill pipe was instrumented and deployed under the drilling vessel to a depth of 1,000ft. The drilling vessel drift was varied relative to the loop current to produce a range of current profiles and surface current speeds. Current loading along the length of the drill pipe was measured using the on-board acoustic doppler current profiler (ADCP).

The paper describes the test set-up and measured VIV response. It includes observations of cross flow VIV, in-line VIV and additional response at higher frequencies not currently predicted with industry VIV analysis tools.

INTRODUCTION

A number of MODU drilling risers in a range of water depths and geographical locations have been monitored over the last 10 years by BP [1]. This monitoring program is part of an on-going commitment to safety and reliability of operations.

Whilst drilling in the Gulf of Mexico in September 2004 operations had to be halted due to excessive loop currents and the riser was retrieved. A standalone motion monitoring system was being used to monitor the drilling riser VIV response.

As currents were not expected to diminish for a number of days a proposal was made to use the time to conduct a test. The proposal was to deploy a length of drill pipe, drift the rig at a range of speeds relative to the loop current and measure the response with accelerometers.

The resulting measurements may be VIV from currents or excitation due to propeller wash from the vessel dynamic positioning (DP) system. Currently our understanding of the effect of propeller wash excitation is limited. Hence, it has been assumed that the response is VIV for the purposes of this paper.

The drill pipe test has provided a valuable full scale VIV data set that complements and extends both existing test data and full scale field measurements. Test findings that do not fit in the industry VIV models have been documented in recent years. Two examples are the occurrence of travelling wave response and higher harmonics. Higher harmonics are response frequencies at integer multiples of the cross-flow and in-line response frequencies. In the set of tests discussed in [3] to [5], higher harmonics were of particular concern in the aforementioned tests as they generated significantly more fatigue damage than the fundamental cross-flow VIV response, which is typically the only response mode considered for VIV design.

This paper will present the test set-up, key results from the test and provide assessments of higher harmonic and travelling wave response.

TEST DESCRIPTION

The drill pipe test set-up is shown in Figure 1. The total length of the deployed drill pipe was 1,080 ft. The drill pipe was 6-5/8 inch OD with 0.492 inch wall thickness. The in-air weight of the drill pipe was 32.2 lb/ft.
Instrumentation

The drill pipe was instrumented with 5 standalone motion loggers distributed along the length as defined in Table 1. A motion sensor was also placed on the drilling vessel itself to help distinguish vessel motion induced response from VIV of the drill pipe. The INTEGRIpod motion loggers used for this purpose are shown in Figure 2. The device can be deployed and retrieved using an ROV and measures accelerations in 3D and angular rates in 2D.

The instrumentation was set to log continuously at a frequency of 10 Hz. This is the sampling frequency typically used for full scale drilling risers with buoyancy diameters in the range of 47 to 56 inch. With hindsight, a higher sampling frequency would have been better, based on the response measured during the test.

<table>
<thead>
<tr>
<th>Logger ID</th>
<th>Depth Below MWL (ft)</th>
<th>x/L</th>
</tr>
</thead>
<tbody>
<tr>
<td>17</td>
<td>Vessel</td>
<td>Vessel</td>
</tr>
<tr>
<td>22</td>
<td>52.0</td>
<td>0.866</td>
</tr>
<tr>
<td>21</td>
<td>443.2</td>
<td>0.503</td>
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<tr>
<td>13</td>
<td>713.2</td>
<td>0.253</td>
</tr>
<tr>
<td>29</td>
<td>848.3</td>
<td>0.128</td>
</tr>
<tr>
<td>14</td>
<td>983.3</td>
<td>0.003</td>
</tr>
</tbody>
</table>

Test Timeline

The test was conducted over a two hour period with a start time of 16:03. During the course of the two hour test the vessel speed was varied with the intention of determining the effect it had on the riser response. The available vessel drift data (over the ground) which was logged manually from the vessel GPS at the times provided is given in Table 2.

The drift observations provide a useful prompt for correlating changes in measured VIV response with the intentional change observed on deck. However, on its own, this information is not of great use. Current measurements, which are the current measurements see by the drill pipe, provide more useful data as discussed below.

The 2 hour test data was broken down and processed in 5 minute intervals. The identification numbers and associated start times for each of the 5 minute intervals are given in Table 3. Four tests are highlighted as they are documented within this paper in detail. These were selected as they each show a different VIV response characteristic.

<table>
<thead>
<tr>
<th>Time</th>
<th>Vessel Drift Information</th>
</tr>
</thead>
<tbody>
<tr>
<td>16:00</td>
<td>Varying vessel drift, speed unknown</td>
</tr>
<tr>
<td>17:08</td>
<td>Vessel drift at 1.8 knots in current direction</td>
</tr>
<tr>
<td>17:17</td>
<td>Reduce drift speed to 0 knot</td>
</tr>
<tr>
<td>17:28</td>
<td>Vessel at 0 knot</td>
</tr>
<tr>
<td>17:38</td>
<td>Increase vessel drift to 1 knot in current direction</td>
</tr>
</tbody>
</table>

Table 2 – Vessel Drift (over the ground), Manual Observations
Table 3 – Test Identification Listing

<table>
<thead>
<tr>
<th>Test #</th>
<th>Start Time</th>
<th>Test #</th>
<th>Start Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>16:03:09</td>
<td>13</td>
<td>17:03:09</td>
</tr>
<tr>
<td>2</td>
<td>16:08:09</td>
<td>14</td>
<td>17:08:09</td>
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<td>16:13:09</td>
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</tr>
<tr>
<td>4</td>
<td>16:18:09</td>
<td>16</td>
<td>17:18:09</td>
</tr>
<tr>
<td>5</td>
<td>16:23:09</td>
<td>17</td>
<td>17:23:09</td>
</tr>
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<td>6</td>
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<td>18</td>
<td>17:28:09</td>
</tr>
<tr>
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<td>16:33:09</td>
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<td>17:33:09</td>
</tr>
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<td>8</td>
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</tr>
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<td>10</td>
<td>16:48:09</td>
<td>22</td>
<td>17:48:09</td>
</tr>
<tr>
<td>11</td>
<td>16:53:09</td>
<td>23</td>
<td>17:53:09</td>
</tr>
<tr>
<td>12</td>
<td>16:58:09</td>
<td>24</td>
<td>17:58:09</td>
</tr>
</tbody>
</table>

MEASURED CURRENT

Current speed and direction was measured from 95ft to 3,700ft below MWL using a vessel mounted Acoustic Doppler Current Profiler (ADCP). The ADCP system provided the average current speed and direction in 10 minute intervals at a range of depths. As the current measurement system was vessel mounted the measurements were inclusive of the vessel drift velocity.

The primary purpose of the current measurement system was to measure the long-term loop current regime. Hence, during vessel transit operations, the current data is typically scrapped as it is contaminated by the current caused by the vessel motion itself. For the purposes of the drill pipe test, the “scrapped” current data was actually the data that was needed: the current speed as seen by the drill pipe. As a result a special request had to be made so that the current data collected during the test period was made available.

The maximum 10 minute average current speed measured along the length of the drill pipe during the test is shown in Figure 3. Individual current profiles that approximately coincide with the four tests evaluated in detail are shown in Figure 4. There is approximately 50ft of missing current data between the vessel keel and the upper most ADCP measurement. Higher current speeds than measured may occur in this region due to the current shear, local amplification as the current flows under the drill ship and the thruster propeller wash.

Figure 3 – Maximum Measured Drill Pipe Current Speed (10 minute average) and Expected Crossflow VIV Frequency, St = 0.20

STROUHAL FREQUENCY

The maximum measured current is used to calculate the maximum expected cross-flow VIV frequency assuming a Strouhal number of 0.20, as shown in Figure 3. The maximum expected cross-flow VIV frequency (Strouhal frequency), varies from 0.6 Hz to 1.1 Hz. Any response frequencies that are identified in the measurements above the Strouhal frequency may be either in-line VIV or higher harmonic VIV response, as discussed in the introduction.

Note that, due to 50 ft of missing current data and the fact that the current is an average of 10 minutes, the actual
maximum measured current and resulting Strouhal frequency may be higher than that calculated.

**DRILL PIPE TEST MODAL RESPONSE**

Modal analysis was conducted on a FEA model of the drill pipe test. The resulting mode-frequency relationship and example mode shapes are shown in Figure 5 and Figure 6 respectively.

As a result of the free hanging test set-up the drill pipe base is unrestrained. This is shown in Figure 6 for the theoretical mode shapes which indicate that the base of the drill pipe would be the location of maximum motion. This is confirmed with the measurements shown in Figure 21 to Figure 24.

![Figure 5 – Drill Pipe FEA Mode vs. Frequency Relationship](image)

**SPECTRAL RESPONSE OBSERVATIONS**

The measured response from each of the four tests highlighted in Table 3 is presented in this paper with three plots as follows:

- Resultant 5 minute acceleration spectra of all 6 instruments;
- X and Y acceleration ‘Waterfall’ plots of the bottom logger. The plots show frequency vs. time with the acceleration amplitude represented as colors where red is the maximum amplitude. The waterfall plots are derived using 512 point (51.2 second) FFTs.

The resulting plots are shown in Figure 7 to Figure 18. Note that the acceleration amplitude scale is different for each test plot and has been removed due to confidentiality. Taking account of the measured current profiles, expected maximum cross-flow VIV frequency and the spectral response of the measured accelerations the following observations are made for each of the tests.

**Test #2**

According to manual observations the rig was varying its drift at unknown speeds during test #2. The measured current direction rotated through 90 degrees along the riser length and varied in average speed from 0.5 to 1.2 knots with a resulting maximum Strouhal frequency close to 0.8 Hz.

The acceleration spectra show a large number of VIV response frequencies ranging from 0.4 Hz up to 2.8 Hz. Some of which are believed to be higher harmonics. Inspection of the waterfall plots shows varying frequency content with time that is likely to be due to the varying vessel drift speed. This varying frequency content has been called time sharing (multiple frequencies participating, but not concurrently) in recent publications [3], [4], [5], [13].

![Figure 7 – Test #2 Acceleration Spectra, All Loggers](image)
Test #5

The measured current during test #5 was similar to that measured during test #2 with a maximum expected cross-flow VIV frequency of 0.78 Hz assuming a Strouhal number of 0.2. The current in the bottom 350ft of the riser ranges from 0.75 knots to 1.0 knots and is 90 degrees to the near surface current of 1.3 knots.

Unlike test #2 the response is relatively stationary in both frequency and amplitude. Three acceleration peaks are observed close to 0.4, 0.8 and 1.2 Hz each a direct multiple of the lowest frequency.

Based on the measured response alone it could be concluded that the peak at 0.4 Hz is cross-flow, the peak at 0.8 Hz is in-line and the peak at 1.2 Hz is the third (cross-flow) harmonic. However, the X and Y waterfall plots do not show a dominant direction at each frequency and based on the Strouhal frequency, cross-flow excitation of the 0.8 Hz peak is a possibility. In addition, the current rotates through approximately 90 degrees between the near surface current and lower drill pipe region. Hence, an alternative explanation is that there is cross-flow excitation at both 0.4 and 0.8 Hz with the cross-flow response at 0.8 Hz being reinforced by the in-line VIV of the 0.4 Hz cross-flow.
Immediately before test #13 the vessel speed was increased to 1.8 knots in the same direction as the current. Based on the measured current this produced a 1.5 knot uniform current along the bottom 500ft of the drill pipe with the sheared near surface current diminishing. The resulting maximum expected cross-flow VIV frequency was 0.92 Hz.

The acceleration spectra show a large number of response frequencies ranging from 0.55 Hz all the way up to 4.65 Hz, Figure 13. The X and Y accelerations, Figure 14 and Figure 15, show some degree of response directionality with frequency. Based on the observed response, a possible explanation of the response is defined as follows:

- Multi-frequency (non time sharing) cross-flow VIV response from 0.55 Hz to 0.7 Hz;
- Multi-frequency in-line VIV response between 1.1 Hz and 1.4 Hz;
- Multi-frequency 3rd higher harmonic response between 1.4 Hz and 2.1 Hz;
- Additional response above 2.1 Hz that is dominant in the Y (in-line) direction, possibly up to the 6th harmonic.

**Test #13**

Immediately before test #13 the vessel speed was increased to 1.8 knots in the same direction as the current. Based on the measured current this produced a 1.5 knot uniform current along the bottom 500ft of the drill pipe with the sheared near surface current diminishing. The resulting maximum expected cross-flow VIV frequency was 0.92 Hz.

The acceleration spectra show a large number of response frequencies ranging from 0.55 Hz all the way up to 4.65 Hz, Figure 13. The X and Y accelerations, Figure 14 and Figure 15, show some degree of response directionality with frequency. Based on the observed response, a possible explanation of the response is defined as follows:

- Multi-frequency (non time sharing) cross-flow VIV response from 0.55 Hz to 0.7 Hz;
- Multi-frequency in-line VIV response between 1.1 Hz and 1.4 Hz;
- Multi-frequency 3rd higher harmonic response between 1.4 Hz and 2.1 Hz;
- Additional response above 2.1 Hz that is dominant in the Y (in-line) direction, possibly up to the 6th harmonic.

**Figure 12 – Test #5 Y Acceleration, Bottom Logger**

**Figure 13 – Test #13 Acceleration Spectra, All Loggers**

**Figure 14 – Test #13 X Acceleration, Bottom Logger**
Test #19
Test #19 exhibits strong, stationary single mode VIV response with higher harmonics. The response identified in test #19 actually occurred in test #18 and 20 from 17:28 to 17:40 in the field measurements. Test #19 is presented as the response exists throughout the entire test duration and is relatively stationary. This duration of response ties in reasonably well with the manual observations taken at 17:28 and 17:38. According to the manual observations the vessel was stationary at this time. The measured current shown in Figure 4 confirms this with less than 0.5 knots of current along the lower 500 ft of the drill pipe. The maximum measured current was 1.8 knots with a resulting maximum Strouhal frequency of 1.1 Hz.

Based on the observed response frequencies and directionality, shown in Figure 16 to Figure 18, a possible explanation of the response is defined as follows:

- Single frequency cross-flow VIV response at 0.55 Hz;
- In-line VIV response at 1.1 Hz;
- Third harmonic cross-flow VIV response at 1.65 Hz;
- Sixth harmonic in-line VIV response at 3.3 Hz.

Whilst this appears to be a plausible explanation based on the observed response it conflicts somewhat with the maximum expected Strouhal frequency of 1.1 Hz, which indicates that the 1.1 Hz response frequency defined above as in-line VIV could potentially be cross-flow VIV.

Even though firm explanations cannot be made for the response, there is clearly higher harmonic response which is currently not accounted for in existing VIV design tools.
VIV AMPLITUDES AND FATIGUE DAMAGE

Displacement amplitudes and fatigue damage values were determined for Test #19 at each individual frequency identified above. Namely: 0.55, 0.1, 0.65 and 3.3 Hz.

The calculated displacement and fatigue damage for each frequency peak is shown in Figure 19. Due to confidentiality, the results have been normalized for this paper where the displacement amplitude or fatigue damage is divided by the maximum from all four frequencies.

The figure shows that both the amplitude and resulting fatigue damage from the in-line response and higher harmonics is less than a tenth of the cross-flow VIV peak at 0.55 Hz.

The fatigue damage does not match with the expected response for a string where curvature would be proportional to the acceleration. This is due to the drill pipe responding as a beam at the higher modes. The transition from tension dominant response to bending dominant response with increasing mode and frequency can be seen in Figure 5.

Based on the calculated fatigue damage values, whilst higher harmonics were observed in the data, they do not appear to be critical from a fatigue design point of view.

STANDING WAVE RESPONSE?

The most commonly used industry VIV design tool is based on the assumption that VIV occurs in standing waves. Recent tests have identified travelling wave VIV response as opposed to standing wave response [5].

Whilst interesting from an academic point of view, the occurrence of travelling wave response has a potential impact on riser VIV fatigue design. A standing wave has regions of negligible displacement and stress (nodes) and regions of maximum displacement and stress (anti-nodes) that are accounted for when calculating VIV fatigue damage.

With a travelling wave response, if a snapshot of the response is taken it will appear to be standing wave. However, as the wave travels, the maximum displacement and curvature occurs at every location along the riser length. This is illustrated in Figure 20 for displacement envelopes. The resulting curvature and/or stress envelope plots will be similar.

As a result of travelling wave response the riser length will experience high fatigue loading along its entire length. Hence, the drill pipe measurements are evaluated with the objective of determining whether the response is standing wave or not.
To determine if the response is standing wave the acceleration peaks (5 minute average) at one of the measured response frequencies of each instrument are extracted and plotted as a function of the drill pipe length. This is conducted for the four tests identified and discussed above. The frequencies from which peaks are extracted for each test are as follows:

<table>
<thead>
<tr>
<th>Test #</th>
<th>Frequency (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>1.108</td>
</tr>
<tr>
<td>5</td>
<td>0.811</td>
</tr>
<tr>
<td>13</td>
<td>0.562</td>
</tr>
<tr>
<td>19</td>
<td>0.552</td>
</tr>
</tbody>
</table>

The resulting plots are shown in Figure 21 to Figure 24. In addition to the measured accelerations, the theoretical acceleration including g-contamination is superposed with the ‘best fit’ mode determined using a least squares approach. Key conclusions identified from these plots are as follows:

- The measured (5 minute average) acceleration response at the selected frequencies has varying amplitude along the length and is close to zero at some of the instrument locations. This indicates the presence of ‘nodes’ and that the response is predominantly standing wave;
- None of the measured accelerations are zero. Hence, it is possible that, whilst the response is mostly standing wave, there could be an additional smaller component of travelling wave response;
- The ‘best-fit’ theoretical modes and the mode vs. frequency relationship match the measured response extremely well up to mode 17.
CONCLUSIONS
As a result of strong team work between BP personnel offshore and in the office and readily available instrumentation, drilling downtime was used to collect a valuable full scale VIV data set.

The test set-up is a free standing system that best represents non-connected risers during temporary operations such as drilling riser rig moves, pipeline installations and running of conductor and casing strings in open water. This should be considered for transfer of conclusions from this drill pipe test to connected riser systems.

As the ‘test’ was impromptu there were some limitations: The current was measured every 10 minutes which was not frequent enough to capture the effect of varying vessel drift. In addition, the drill pipe monitoring system sampling frequency and the number of instruments could have been higher.

The drill pipe test data complements and extends existing high mode test data collected by the industry.

VIV response was observed during the test that may have been VIV from currents or possible excitation due to propeller wash from the vessel dynamic positioning (DP) system. Currently our understanding of the effect of propeller wash excitation is limited and the response has been assumed to be due to current.

The response was found to be predominantly standing wave for frequencies up to 1.11 Hz, which corresponds to a mode number of 17. In addition, the measured response matched well with the modal response determined using FEA. These findings match those from a 6,000ft connected drilling riser up to mode 10 [1].

Higher harmonics up to six times the cross flow VIV frequency were observed. This test combined with the findings from previous tests [3] to [5] and full scale drilling risers [1] confirm the occurrence of higher harmonic response although the resulting fatigue damage does not appear to be critical from a design point of view. The test results also confirm that there is still room for improving the industry understanding of VIV and the associated analysis tools.

On this basis, where next? From a riser design point of view more data is needed for full scale production riser systems. However, as these are commonly straked to mitigate VIV, the greatest risk from higher harmonic VIV or propeller wash excitation may actually be to shorter term operations conducted in high currents including drilling riser installation and rig moves, pipeline installations and running of conductor and casing strings in open water.

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REFERENCES


