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ACTUAL VIV FATIGUE RESPONSE OF FULL SCALE DRILLING RISERS: WITH AND WITHOUT SUPPRESSION DEVICES

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ABSTRACT

In an effort to more effectively understand and manage vortex-induced vibration (VIV) fatigue integrity of its drilling risers, BP has instrumented several of them on a number of mobile offshore drilling units (MODUs) and offshore production platforms worldwide. This paper presents several aspects of the findings from those monitoring campaigns, with particular emphasis on the relatively more densely populated MODU data sets. In-situ monitoring has practical use as a real-time quantifier of accrued VIV fatigue damage to both drilling riser and wellhead casing over the course of a given monitoring period, a fundamental indicator of structural integrity. At present, this can be very useful to operators given that the gap between predicted and measured VIV fatigue damage can be very large. In this paper, the measured data are used to expose some of the physical details of full-scale riser response whose omission from predictive design tools and methods may contribute to this wide gap. To characterize the size of the gap, the data are compared to calculations using the most commonly used industry VIV analysis software. This demonstrates the inherent level of analysis over conservatism with respect to full-scale, unsuppressed drilling risers in the field when typical analysis parameters are utilized. A means of adjusting the parameters to reduce the over conservatism is then implemented. Finally, the data are used to reveal some performance indicators for VIV suppression devices that are presently being utilized in drilling operations.

INTRODUCTION

Over the past several years, dating to the late 1990s, BP, in support of an overall commitment to safety and reliability of operations, has undertaken an extensive assurance initiative for the purpose of assessing and maintaining structural integrity for offshore drilling risers. This effort has included in-situ, full-scale monitoring of drilling riser VIV response during several MODU drilling campaigns. The targeted benefits are twofold: (i) quantification of actual measured fatigue damage ensures that drilling risers are being operated in a safe and prudent manner; (ii) improving the understanding of drilling riser behavior in high currents provides a path to a more predictable and, hence, safer position to be taken on the engineering conservatism applied for operations.

In the Gulf of Mexico (GoM), high loop currents can delay drilling and completion operations and the resulting cost to operators is high. This places a high priority on better understanding how drilling risers actually behave while subjected to high currents. This is amplified in importance when considering that for six months of the year high currents can occur in combination with GoM hurricane activity.

The measured response data provide insight regarding the underlying physics of VIV at full scale and suggest avenues via which the current analysis approaches may be revised to more accurately capture them. For model-scale bare and helically-straked flexible pipes, Tognarelli, et al. [7] and Frank, et al. [2] extracted several underlying physical details of the flow-induced response from hydrodynamic laboratory tests for comparison to modeling assumptions. Similarly, the Deepstar joint-industry project conducted towing tests of even higher aspect ratio, small-diameter pipes with and without VIV suppression in the Gulf Stream. Several of the findings from these tests regarding underlying physics have been presented in papers by Jaiswal & Vandiver [3], Jhingran & Vandiver [4], and Marcollo, et al. [5] Herein, we will compare and contrast full-scale findings to some of these model-scale results.

Beyond confirmations of safe operations during the monitoring periods and revelations of physical details, the findings of the MODU monitoring campaigns begin to quantify the overall gap between the predictions of state-of-the-art VIV fatigue analysis tools and actual field measurements. Analytical VIV fatigue damage prediction tools are widely recognized by the industry as conservative. Recently, comparisons between measured and calculated damage have been made by others using the aforementioned long, flexible cylinder experiments at relatively low Reynolds number (Re) and limitations of the software were noted. ([3], [4], [5], [14]) However, to-date the degree of analysis conservatism compared to full-scale measurements in more realistic Re ranges has not been extensively demonstrated. Shilling, et al [6] utilized full-scale drilling riser VIV response data measured outside the GoM to illustrate the conservatism of analysis tools and propose a calibration method. They further recommended the extension of the monitoring and calibration effort to include data from the high-current-prone GoM with the expectation that this would extend the study to deeper water, higher flow speeds and higher-mode response.

This paper includes the data from [6] and follows their recommendation, adding several more data sets collected from drilling risers during operations in the GoM. The monitoring campaigns in [6] and those discussed herein span a range of real flow regimes up to a Re of about $2x10^6$. The collected set of full-scale measurements is again compared to analyses undertaken with industry available tools. Analyses are performed using typical industry parameters as well as an adjusted set of parameters aimed at reducing the level of over prediction. The findings of these comparisons are presented and discussed with a view to establishing a better understanding of the resultant levels of operational conservatism.

The paper finally details the findings of several monitoring campaigns on operating full-scale drilling risers with partial coverages of VIV suppression: either Shell Global Solutions, Inc. (SGSI) fairings or Lankhorst fins as shown in Figure 1 and Figure 2 respectively. Qualitative comparisons between full-scale measured response data and suppression performance expectations are made. However, comparison to the analysis tools is not undertaken since general indications are that the present VIV fatigue damage calculation programs do not include the physics of VIV suppression. In and of itself, this is a key indicator of the need to improve understanding and analysis since the results of VIV analysis are often used to determine whether (and to what extent) suppression devices are necessary. A companion paper [8] gives greater detail on the performance of existing and emerging VIV suppression devices and the need for further development from an operations perspective (i.e., design of devices for ease and quickness of installation, handling and storage).

Figure 1 – (top) Full wrap fairings; (bot) Tailfin fairings.

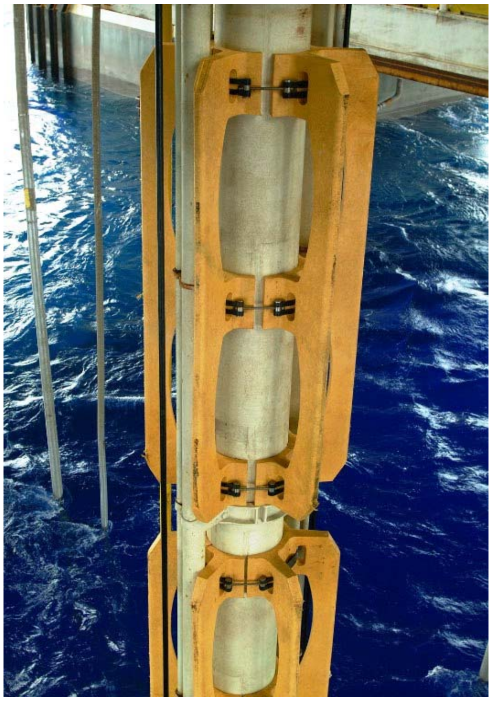

Figure 2 – Lankhorst Fins on Drilling Riser

THE DRILLING RISERS

The set of drilling risers from which data are included in this paper are shown in Table 1. They cover a range of water depths from 1,182 ft – 6,800 ft and a range of geographic locations. In three cases, devices external to the riser joints were utilized to suppress VIV. These data sets, given in the last three rows of the table, will be discussed separately from those without VIV suppression devices. The primary measurement devices are accelerometers, with strain gauges used in a few cases. In all cases, the current profile was also measured. The instrumentation will be discussed in more detail in a later section.

Riser #	Water Depth (ft)	Buoyancy Diameter (inch)	VIV Suppression	Riser Instrumentation
1	1,181	47.5	None	7 accelerometers
2	3,510	55	None	12 accelerometers
3	3,166	55	None	12 accelerometers
4	3,172	56.5	Staggered Buoy/Slick	6 accelerometers
5	5,434	56.5	Staggered Buoy/Slick	6 accelerometers
6	6,000	52	None	14 accelerometers
7	6,800	53	Staggered & Fin Joints	20 accelerometers, 5 strain stations
8	4,600	50	Fairings	10 accelerometers, 1 strain station
9	4,065	48.7	Fairings	10 accelerometers

Table 1 – Summary of BP Monitored MODU Drilling Risers

A typical drilling riser stack-up is given in Figure 3 for a riser without suppression devices. The submerged portion of the riser consists primarily of buoyant joints, to offset the riser's weight and reduce the demand on the tensioning system. Buoyant joints have a nearly circular cross-section. Above and below the section of buoyant joints, there are usually relatively fewer slick (non-buoyed) joints that have a less regular cross section consisting of the riser main tube and multiple cylindrical auxiliary lines. From time to time, joint types are alternated or staggered as a means of suppressing VIV. When applicable, this has also been noted in Table 1.

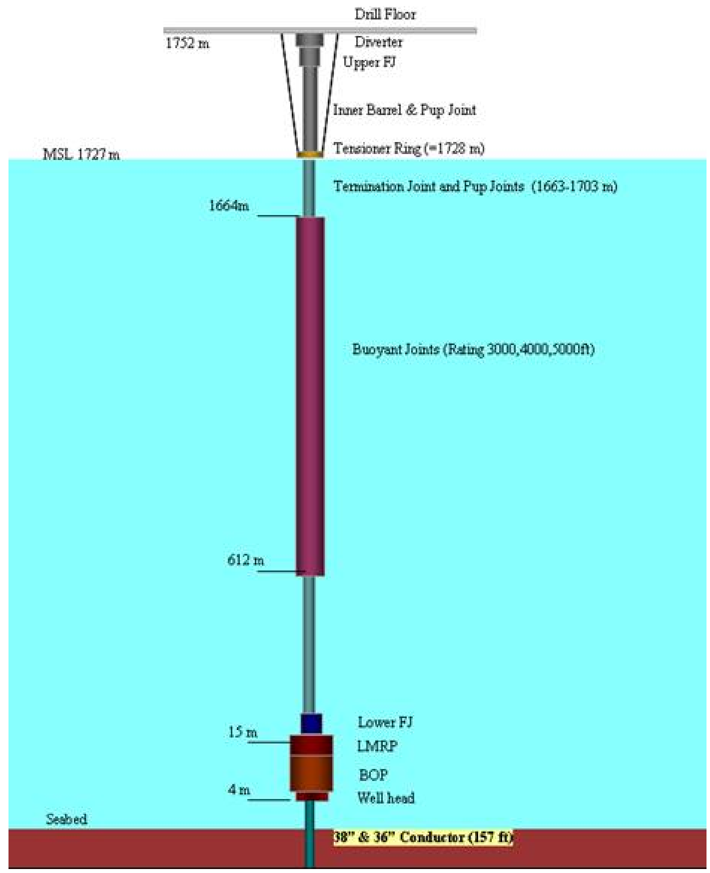

Figure 3 – 6,000 ft Water Depth Gulf of Mexico Drilling Riser

INSTRUMENTATION

BP's MODU drilling risers have been instrumented with standalone motion and strain measurement devices. The instrumentation used is shown in Figure 4 to Figure 6. Standalone monitoring systems are simple, reliable and relatively low-cost. However, they do have limited battery life. Thus, data is collected 15 minutes every two hours, sampling data at 10Hz. This allows over three months of data to be captured before a battery change is required.

An *INTEGRIpod* motion logger from 2H Offshore, Inc. is shown in Figure 4. The device can be deployed and retrieved using an ROV and measures 3D accelerations and 2D angular rates. The motion logger placement along the riser length is optimized to capture the entire range of modes expected during the operation.

An *INTEGRIstick* strain sensor from 2H Offshore, Inc. is shown in Figure 5. The device is strapped to the outside diameter of the riser and measures the change in riser curvature in two planes. The proving ring strain sensor from Fugro Structural Monitoring is shown in Figure 6. A set of four proving rings are mounted around the circumference of the riser to also provide measured strain in two planes.

In addition to the instrumentation installed on the riser string, a motion sensor is also generally placed on the drilling vessel itself. This helps to distinguish vessel motion induced response from VIV of the riser. A motion sensor is also typically placed on the LMRP/BOP stack to identify whether VIV motions are being transmitted to potentially fatigue sensitive locations on the conductor and casing strings, such as welds and connectors.

Figure 4 – INTEGRIpod Motion Logger

Figure 5 – INTEGRIstick Strain Sensor

Figure 6 – Fugro Proving Ring

DATA PROCESSING APPROACH

As mentioned, the MODU drilling risers documented in this paper were all instrumented using standalone accelerometers with supplemental strain monitoring on 2 of the risers. The data processing of the riser acceleration response data is conducted using a frequency domain approach. A brief summary of the processing stages is given below, [6], [10] and [11].

1. Conduct spectral analysis at each motion sensor location;
2. Identify the peak response frequencies above a threshold measurement level determined based on VIV design;
3. Correlate the response from all the motion sensors along the riser length at each peak response frequency;
4. Assume normalized theoretical mode shapes predicted by finite element analysis (FEA) for the as-installed riser configuration;
5. Using linear regression analysis identify the shape and amplitude that provides the best-fit shape through the measured response peaks along the riser, [12];
6. Re-construct the riser shape based on the mode shape and amplitude determined from shape matching;
7. Compute stresses along the riser from the re-constructed mode shape.

This approach provides all the significant response frequencies and associated modes, vibration amplitudes, stresses and fatigue damage. The limitation of the stated approach is that it assumes the response is both standing wave and non-time-varying. To minimize potential inaccuracies resulting from these assumptions the instrumentation is typically clustered near the top and bottom of the riser, where local standing wave response is most likely as a result of the boundaries, and the data processing duration is optimized to account for any time-varying VIV frequency or amplitude. In addition, strain measurement complements acceleration measurement and has been used and is recommended for validation of findings.

It should be noted that whilst there are limitations of the stated approach, the observed VIV of full-scale drilling risers to date typically tends towards standing wave and non-time-varying response with increasing VIV amplitude. Example shape matching plots of riser #6, a 6,000ft drilling riser, responding in modes 5, 7 and 10 are shown in Figure 7, Figure 8 and Figure 9, respectively. The red line represents the theoretical mode shape determined from global FEA and modal analysis. The blue data points are actual measured acceleration peaks at the frequency of peak measured response. As an example, the measured acceleration peaks shown in Figure 7 are extracted from and can be seen in Figure 10, which is described in more detail below, at an approximate frequency of 0.09Hz. It can be seen that the theoretical modes match the measured VIV response well in these cases.

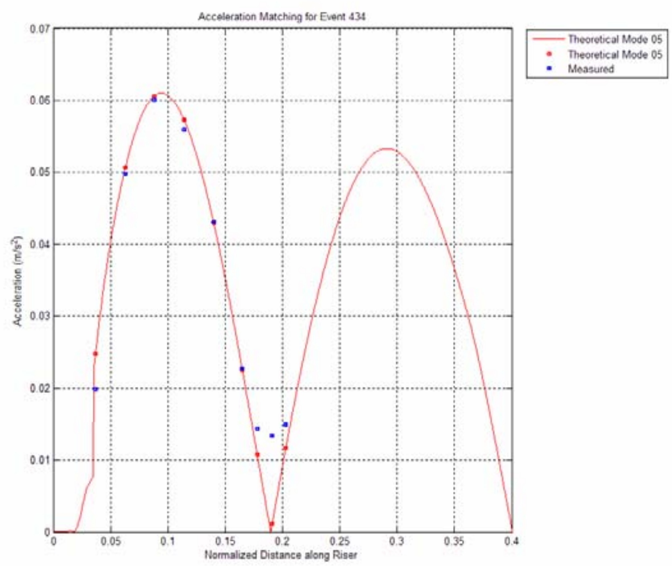

Figure 7 – Example Mode 5 Shape Matching for Bottom 2,400ft of a 6,000ft Drilling Riser

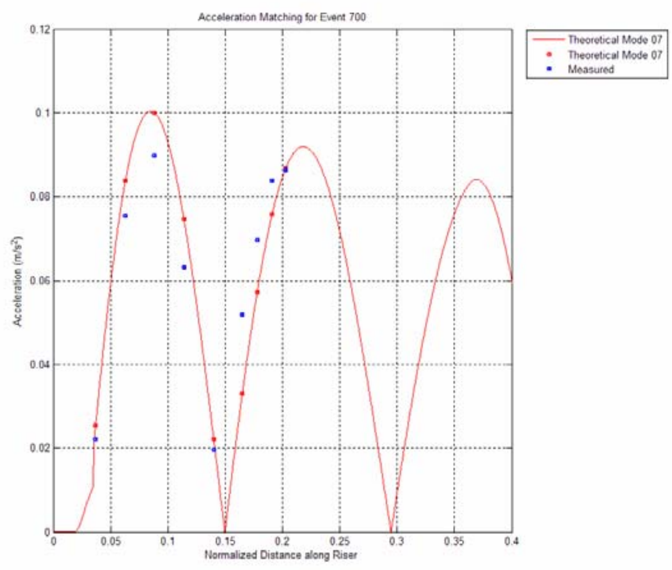

Figure 8 - Example Mode 7 Shape Matching for Bottom 2,400ft of a 6,000ft Drilling Riser

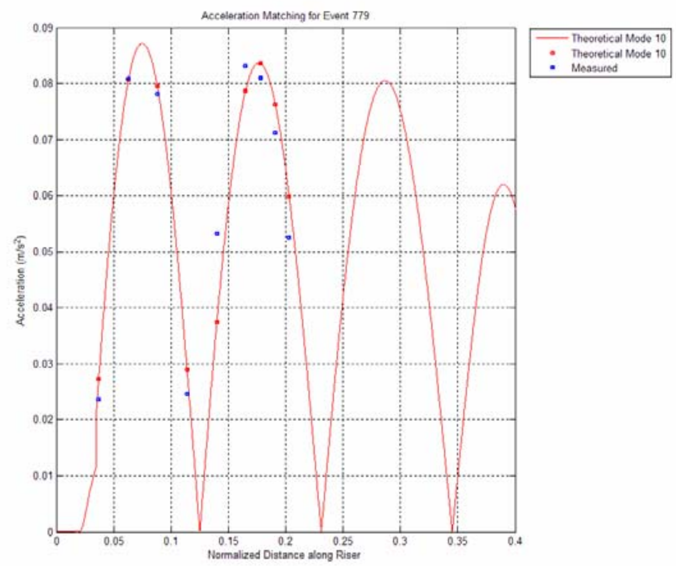

Figure 9 - Example Mode 10 Shape Matching for Bottom 2,400ft of a 6,000ft Drilling Riser

IDENTIFICATION OF MEASURED VIV

The measured riser response may be caused by a number of sources such as: VIV, wave excitation, drilling induced vibrations or even an unknown excitation source. Identifying VIV response is based on a common-sense interpretation of the power spectra of the measured data. Factors that are considered during the VIV identification process are:

- VIV is typically a narrow-banded response, whereas, wave-induced motion is broader-banded;
- Cross-flow VIV response frequencies should correlate to measured current speeds according to the Strouhal relationship;
- Vessel motion contamination can be identified and discarded by correlating spectra of measurements along the riser with those measured on board the vessel;
- Drilling induced vibrations typically occur at higher-than-VIV frequencies equal to the drill string rotation speeds. Further, drilling activities are documented in the daily operations reports.

FULL-SCALE VIV RESPONSE OBSERVATIONS

State of the art analysis tools have until very recently contained the assumption that VIV occurs in standing waves and may be single-mode or multi-mode, where multiple response modes and frequencies are present in the aggregate response concurrently. Both of these behaviors were observed in unsuppressed flexible pipe tests discussed in [7]. More recent tests have also shown travelling wave response as opposed to standing wave response, time sharing (multiple frequencies participating, but not concurrently) and the occurrence of higher harmonics [3], [4], [5]. 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 as they generated significantly more fatigue damage in the test data than the fundamental cross-flow VIV response , which is typically the only response mode considered for VIV design.

The full-scale field measurements provide an ongoing means of confirming or otherwise the relevance of the model test findings for real riser system VIV design. The field measurements show that to the extent that they can be captured, many of the phenomena seen in the test data are also identified at one time or another in full-scale drilling riser response. A range of example spectra plots demonstrating this, all from the same riser (#6) in 6,000ft during a one month monitoring period, are included as follows:

- Single mode cross-flow response, Figure 10;
- Concurrent multiple mode cross-flow and in-line response, Figure 11;
- Mode time sharing (multiple frequencies participating but not concurrently), Figure 12;
- Higher harmonics, Figure 13 and Figure 14;
- Possible dominant higher harmonics, Figure 15;

Key supplementary findings from drilling riser VIV monitoring are related to: the probability of occurrence of VIV, measured VIV amplitudes, travelling waves, mode time sharing and higher harmonics. Each of these is discussed further in more detail below.

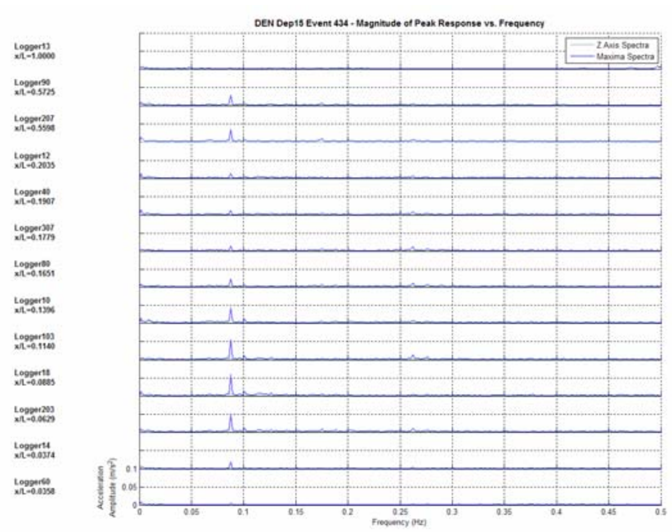

Figure 10 – Acceleration Amplitude Spectra Plots Showing Single-Mode Cross-flow VIV Response

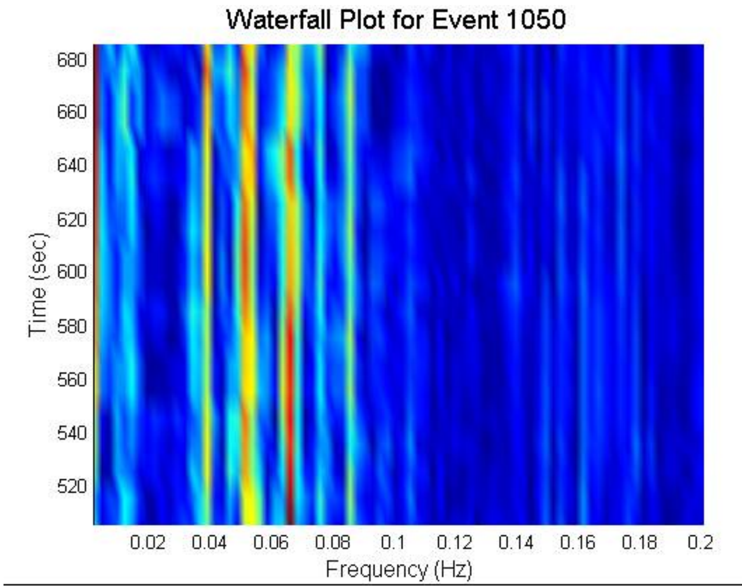

Figure 11 – Acceleration Waterfall Plot Showing Multi-Mode Cross-flow and In-line VIV

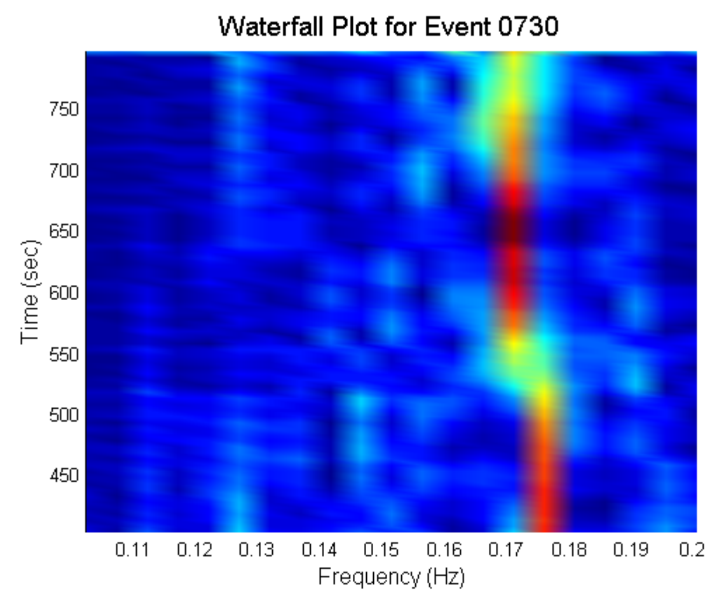

Figure 12 – Acceleration Waterfall Plot Showing Time Sharing

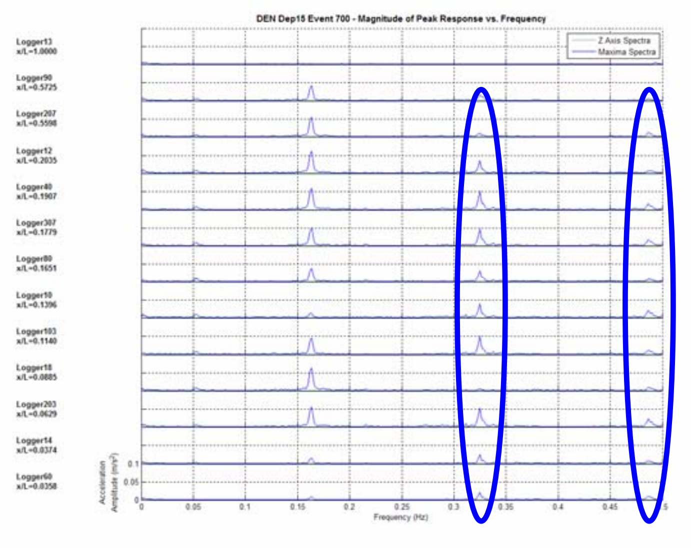

Figure 13 – Acceleration Amplitude Spectra Plots Showing In-Line and Higher Harmonic Response

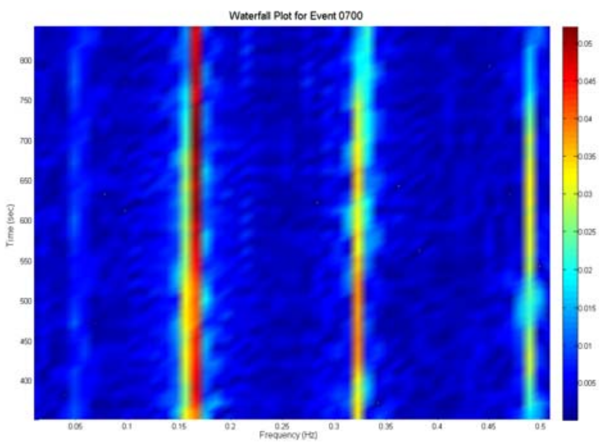

Figure 14 – Acceleration Waterfall Plot Showing Cross-flow, In-Line and Higher Harmonic

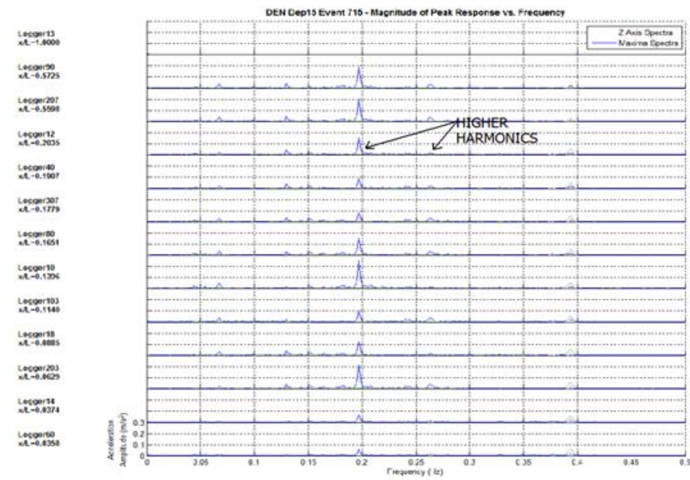

Figure 15 – Acceleration Amplitude Spectra Plots Showing Possible Dominant Higher Harmonic Response

Probability of VIV Occurrence

Analysis tools typically predict that VIV will occur in deep-water risers close to 100% of the time when current speeds are sufficiently high to excite the first natural mode or higher. By contrast, findings from the various drilling riser monitoring campaigns discussed in this paper tend to indicate that despite the presence of currents that could excite VIV, VIV does not occur all the time. Depending on the riser type and the presence of suppression devices, drilling riser VIV is observed between 2% to 26% of the time that measurements are taken, as shown in Figure 16. This equates to 2% to 26% of total time assuming that the measurements are taken often enough.

At the time of writing, work is on-going in an effort to identify which parameters trigger VIV. Preliminary findings show that, perhaps not surprisingly, VIV occurrence increases with increasing current speeds, lower current shear and low wave energy. However, no single parameter identifies VIV or the lack of and a requirement for a statistical approach is expected to correctly represent the parameterization.

The effect of the difference between the percentage occurrence of VIV in the field and with VIV design tools is discussed further below as part of the comparisons between SHEAR7 predictions and measurements.

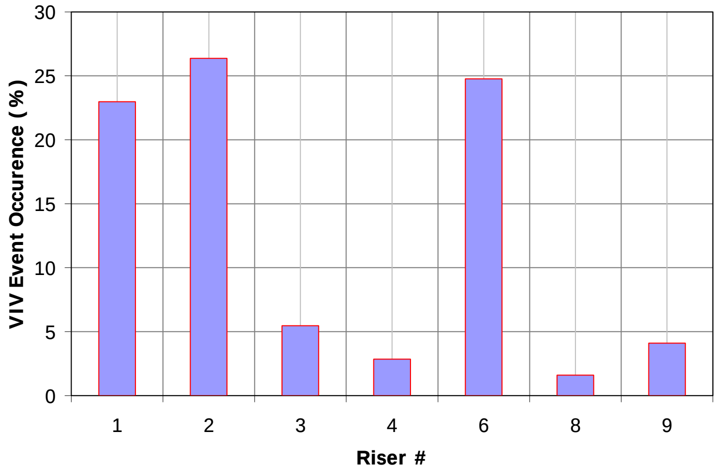

Figure 16 – Probability of VIV Occurrence

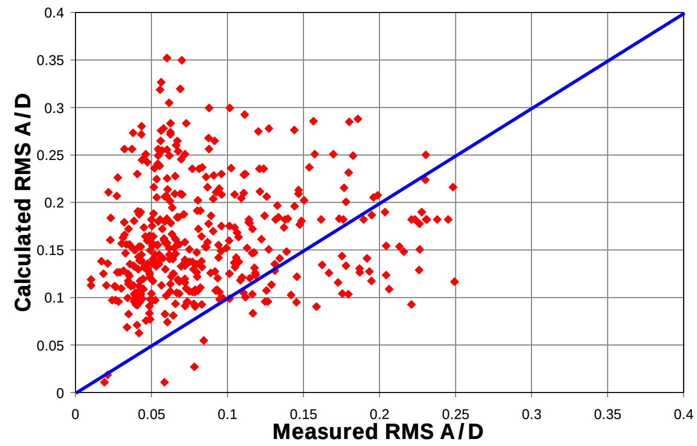

Figure 18 – Calculated vs. Measured Maximum Measured RMS A/D

Measured VIV Amplitudes

Maximum measured RMS A/D values for a 6,000 ft drilling riser in a range of current speeds up to 2.7 knots are shown in Figure 17. The plot shows that VIV amplitudes tend to decrease with increasing frequency and do not exceed 0.3 diameters during the monitoring interval.

The measured A/D values are also plotted against the corresponding estimated A/D values determined using SHEAR7(v.4.4), measured current profiles and the "Adjusted" parameters described below, as shown in Figure 18. The comparison shows that the calculated A/D values are greater than the measured and that there is a large amount of scatter in the comparisons. Some of the scatter identified in comparisons of measured and calculated VIV amplitudes may be due to the VIV design tool, but the majority of scatter is believed to be due to the phenomena itself. This is discussed further below in the comparison of VIV measurements to analysis predictions.

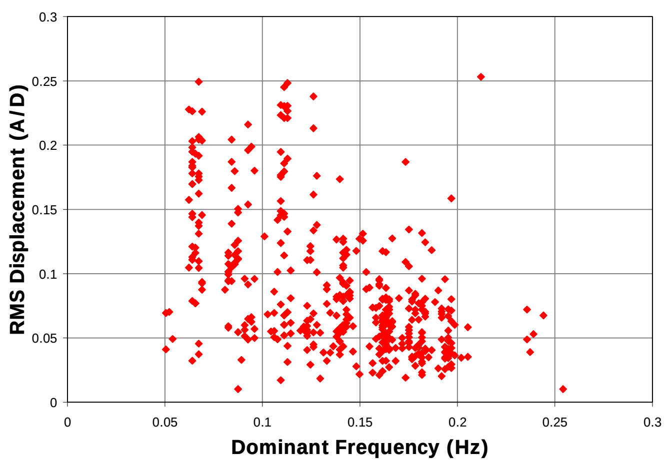

Figure 17 – 6,000ft Drilling Riser, Maximum Measured RMS A/D vs. Frequency

Travelling Waves

Travelling wave response has been identified in high mode VIV tests [5]. Theoretically, if the response is 100% travelling wave as opposed to standing wave then there would be no nodes and anti-nodes along the riser length and the displacement or acceleration envelope would be fairly constant.

The field measurements show standing wave response in the bottom 25% of a 6,000ft drilling riser up to mode 10 as shown in Figure 7 to Figure 9. However, as discussed earlier the instrumentation is placed to capture the local standing wave response that is most likely near the boundaries. Subsequent monitoring campaigns include instrumentation more appropriately placed to capture any travelling wave behaviour should it occur.

Mode Time Sharing

The latest version of the most commonly used industry VIV design tool SHEAR7(v.4.5) has been developed to account for the concept of time sharing of modes (multiple frequencies participating, but not concurrently) [13]. Time sharing was observed in the set of model tests discussed in [3], [4], [5].

The full-scale field measurements were reviewed to identify the occurrence or absence of time sharing in drilling risers. Time sharing is observed in the field measurements, whilst the riser was hung-off, as shown in Figure 12. However, single mode and multi-mode response (multiple frequencies participating simultaneously) is also seen as shown in Figure 10 and Figure 11 respectively. Whilst the percentage occurrence of each type of response has not been determined, the observed VIV of full-scale drilling risers shows that the largest amplitude and resulting fatigue damage responses, which are expected to be most critical for VIV design, are typically associated with single-mode behavior.

Higher Harmonics

Existing industry-standard analysis tools only consider cross-flow VIV associated with vortex shedding at (1X) the Strouhal frequency. They do not consider in-line vibrations at twice this frequency nor do they treat higher harmonic response at 3X, 4X, 5X, etc., the Strouhal frequency. Refs. [4] and [14] indicate that for model-scale tests on unsuppressed pipe, higher harmonic excitation can increase the fatigue damage by 1-2 *orders of magnitude* over the cross-flow VIV fatigue damage that occurs solely at the Strouhal frequency. Ref. [5], which considers a subset of these tests, indicates that higher harmonic response may not be oriented circumferentially with cross-flow or in-line response and that this should be accounted for when assessing the true impact on damage of higher harmonics.

The aforementioned observations pertain to experiments with circular cross-sections in somewhat idealized uniform and sheared flow conditions at relatively low Reynolds number. Hence, in an effort to increase our understanding of the significance of higher harmonics in actual drilling risers, the drilling riser field measurements have been processed in order to identify the presence of higher harmonics and the fatigue damage contribution. The approach used to identify higher harmonics is summarized as follows:

- If available, the maximum measured current, riser diameter and Strouhal number assumption of 0.20 is used to estimate the highest possible cross-flow VIV excitation frequency;
- All measured frequency response peaks are collated and ranked;
- If frequencies are identified at multiples (2X, 3X, 4X etc) of another they are categorized accordingly;
- The calculated Strouhal frequency is used to check if peaks identified as in-line or higher harmonic response may also be cross-flow VIV.

Based on this methodology, the % occurrence of in-line vibrations and higher harmonic response and the resulting fatigue damage is determined. The results showed that both in-line and higher harmonics response, were often observed during the monitoring of connected drilling risers. However, their contribution to the total VIV fatigue damage to the riser was relatively small. This is shown in Figure 19 and Figure 20.

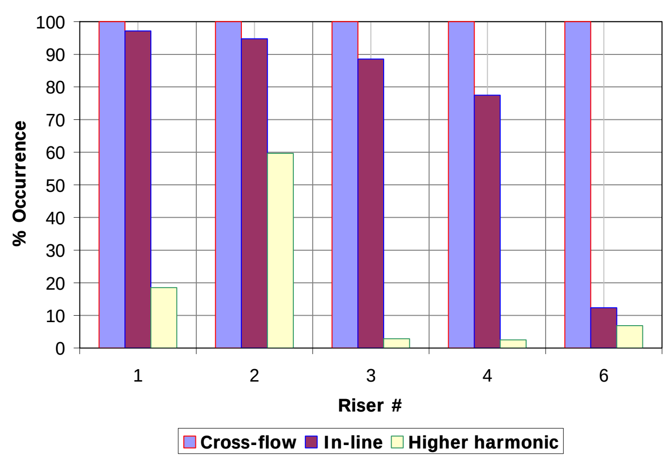

Figure 19 - % Observations of Cross-flow, In-line and Higher Harmonic VIV Response in Monitored Risers

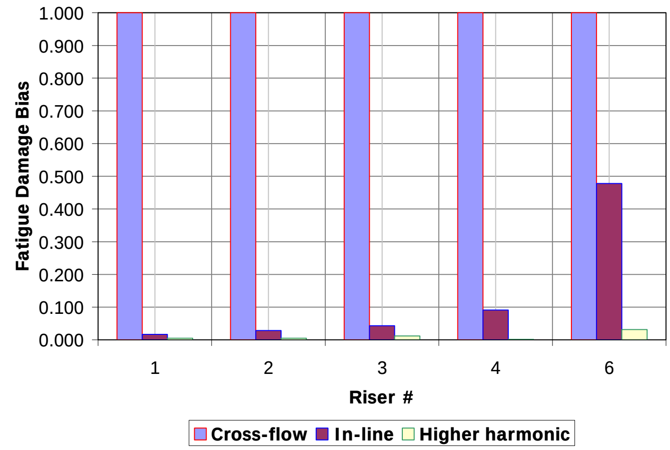

Figure 20 – Fatigue Damage Contribution of In-line and and Higher Harmonic VIV Compared to Cross-flow VIV Fatigue Damage

By contrast, inline vibrations and higher harmonics accounted for a much larger proportion of the VIV fatigue damage during hung-off operations. The fatigue damage accumulation of a hung-off 6,000ft drilling riser is shown in Figure 22. At the start of the 11th June a step change increase in the accumulated fatigue damage can be observed. This coincides with the acceleration response spectra shown in Figure 15 which has been classified as possible dominant higher harmonic response. The reason for defining the response as dominant higher harmonic is the presence of smaller peaks at 1/3 and 2/3 the dominant peak. The reason for defining it as "possible" is that there was no current measurement at the time which would have allowed confirmation or otherwise whether 1X cross-flow response was possible at that frequency. The discussed response occurred during a rig move operation and unfortunately the current measurement system had been retrieved for maintenance at the time that it occurred.

Perhaps not coincidentally, the situation in which the riser is hung-off, is the full-scale scenario that most closely reflects the model tests documented in [4], [5] and [14]. In the hung-off scenario, the riser has been disconnected from the wellhead and is suspended under its own weight and that of the massive BOP and LMRP at its bottom end. Similarly, the model tests consisted of a towed pipe with a large weight at the bottom end to provide tension.

VIV FATIGUE DAMAGE IN CONNECTED OPERATIONS

An example of the fatigue damage accumulated, at the location of maximum accumulated fatigue damage, during a drilling campaign in which high currents were observed is given in Figure 21. In this particular case, measured currents reached maximum speeds of 2.7 kts. This corresponds to a Reynolds number with respect to the buoyant joint diameter of about $2x10^6$. However, the VIV fatigue damage to the riser was negligible as was the fatigue damage in the conductor and casing string for a well drilled during this campaign.

Noting that the fatigue damage accumulation is negligible, it can be seen in Figure 21 that the greatest fatigue damage accumulation rates do not always coincide with the periods of maximum current. This is believed, in part, to be due to the current profile shape. The fatigue damage was highest in the currents that were less sheared, for which higher current loading occurred on the continuous buoyancy region of the drilling riser.

This riser was not fitted with any VIV suppression devices. In general, VIV fatigue damage during connected operations was far less than that which would have been predicted by state-of-the-art engineering analyses as discussed below.

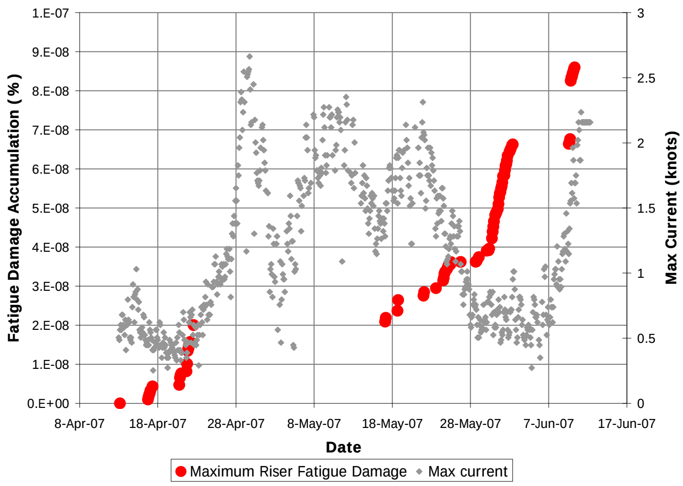

Figure 21 – 6,000ft Connected Drilling Riser, Accumulating Fatigue Damage

VIV FATIGUE DAMAGE DURING HUNG-OFF OPERATIONS

During hung off operations, VIV fatigue damage can build at a much greater rate than when the riser is connected. This is shown in Figure 22 and is believed to be due to a number of factors such as the reduced tension, the fact that the continuous buoyancy is closer to the surface, rig move operations and the occurrence of higher harmonics.

The fatigue damage accumulation shown in Figure 22 is actually at the same location as that given in Figure 21 and occurs during a 3-4 day period when the riser was hung-off and the rig was moved between wells. Key observations from Figure 21 and Figure 22 are that the fatigue damage accumulation is 5-6 orders of magnitude more severe during hang-off than when connected. In addition, as discussed in the higher harmonics section above. The majority of the hung-off fatigue accumulation may be due to higher harmonic response during rig move operations.

VIV fatigue damage rates were also observed to be relatively high during some full-scale towing of freely-hanging drill pipe [1]. Compared to a drilling riser, drilling strings are much smaller diameter (6-5/8 in) and have a simple cylindrical cross-section along their entire length.

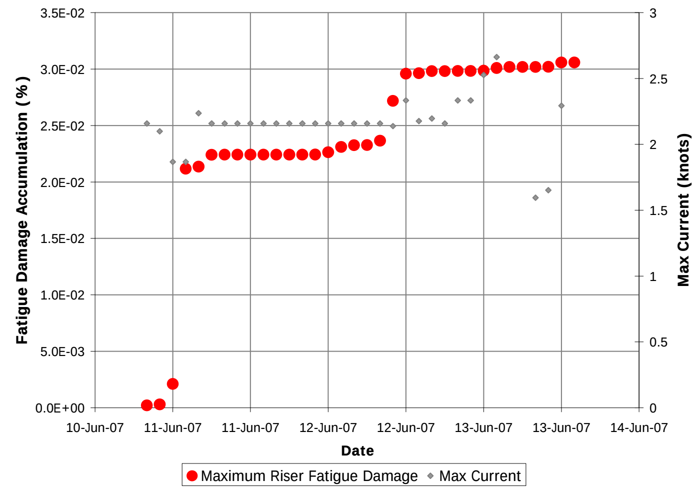

Figure 22 – 6,000ft Hung-Off Drilling Riser, Accumulating Fatigue Damage

COMPARISON OF VIV MEASUREMENTS TO ANALYSIS PREDICTIONS

In general, measurements have indicated that VIV fatigue in drilling risers and casing strings is building at a much lower rate than would be predicted by the current industry VIV design tool, SHEAR7 (version 4.4 at the time of these analyses). This is exemplified in Figure 23, which shows that for an unsuppressed drilling riser in any given current profile, using recommended default analysis parameters, the maximum fatigue damage anywhere on the riser is over predicted by an average factor of roughly 30. This is without including any factor of safety and does not consider the whole life of the riser, during which the location of the point of maximum damage would certainly change as current profile shapes and speeds change. It also does not consider the fact that, as mentioned above, measurements reveal that VIV does not occur during a large percentage of flow conditions in which analysis tools indicate that it should occur.

Describing Figure 23 in more detail, each data point represents the software-calculated maximum fatigue damage rate along the riser length using measured current data plotted against the same quantity recorded during the corresponding 10-minute field measurement. The locations of the point of maximum damage rate do not necessarily coincide between the calculated and measured quantities; however, selected co-located point-to-point comparisons yielded similar results. The fatigue damage rate has been normalized to the maximum fatigue damage rate of all data. The different colors represent the risers without fairings (1 – 6) defined in Table 1.

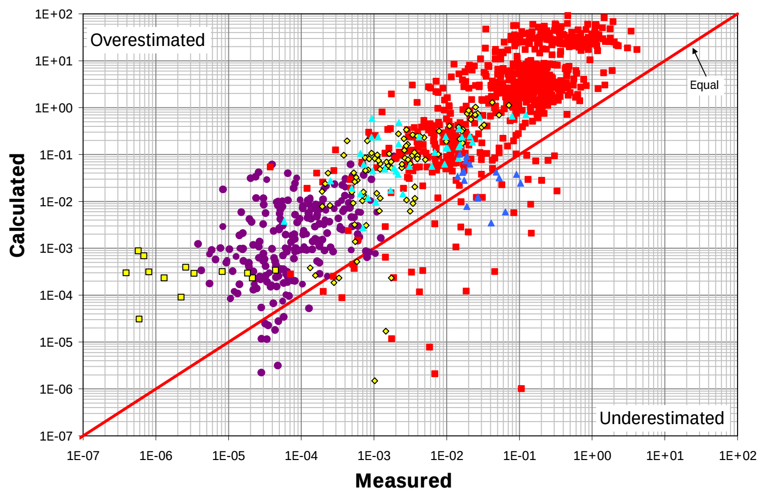

Figure 23 – Measured vs. Calculated Normalized Maximum Fatigue Damage, Typical Design Parameters

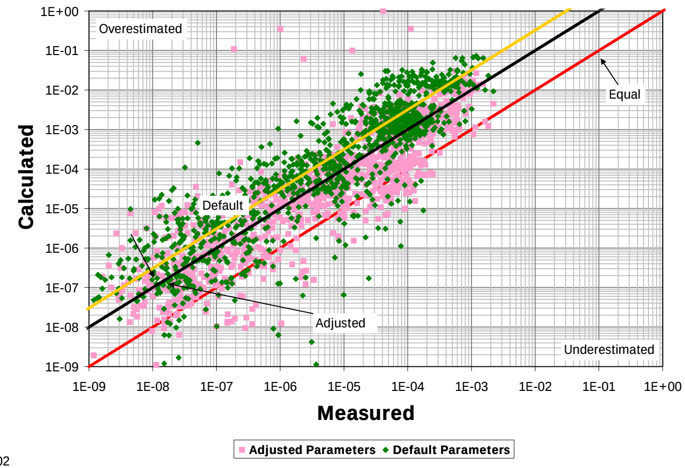

Figure 24 – Measured vs. Calculated Normalized Maximum Fatigue Damage for All Risers with "Adjusted" Parameters and Typical Design Parameters

While it is good news that the VIV design tool and analysis parameters typically used by the industry at this time are on average conservative by a factor of 30 for connected drilling riser fatigue damage, Figure 23 also emphasizes the large gap that still exists between the current understanding of VIV and reality. This gap is characterized not only in the mean overprediction but also in the broad scatter of the data, which indicates that despite on-average conservatism, the possibility still exists to under predict in certain scenarios. Failing to understand the nature of this gap limits our prediction confidence and thus our ability to precisely design to a particular factor of safety. It also limits our ability to prescribe what, if any, VIV mitigation and/or drag reduction devices may be warranted to maintain integrity and extend operability.

To some extent, VIV programs can be calibrated to yield a lower average overprediction (bias) by adjusting analysis parameters within reasonable ranges. In Figure 24, this approach has been taken to reduce the average fatigue damage bias from a factor of 30 to 10. Key changes are the use of a Strouhal number of 0.20 instead of CODE200 and a 50% reduction in the maximum lift. However, there seems to be no physically supportable manipulation of parameters that yields an average bias of one (i.e., prediction, on average, equal to measurement) nor is there a set of parameters that limits the considerable scatter observed in the data. It is this scatter, in particular, that limits confidence in predictions. Indeed, if we were to implement a parameter set, supportable or not, that would reduce the average bias to one, we would clearly run a large risk of under predicting fatigue damage in a much higher percentage of cases than we would if we accept an average bias of ten.

Some of the scatter identified in comparisons of measured and calculated fatigue damage may be due to the VIV design tool, but the majority of scatter is believed to be due to the phenomena itself. One reason for the large amount of scatter may be the aforementioned physical phenomena observed in both model-scale and full-scale measured data that are not modeled in the analysis programs. Another may be the inherent stochastic nature of the loading processes which is not currently captured in analysis models. Yet another may be details of the nonlinear VIV phenomenon that remain undiscovered.

In any case, there are limits to how confidently we can predict VIV fatigue damage using industry-standard analysis models with acknowledged shortcomings. The knowledge of these shortcomings should be considered when selecting factors of safety for design and VIV analysis methodology details such as the minimum acceptable number of current profiles to use for determining long-term VIV fatigue damage. To get beyond these limits, it is prudent to consider alternative models that appropriately reflect the learnings from both experimental and monitoring campaigns.

VIV SUPPRESSION DEVICE PERFORMANCE

Fairings. As indicated in Table 1, in two cases VIV response data were collected from drilling risers fitted with fairings in the upper part of the water column, where loop current speeds are generally the highest. The role of fairings is to suppress VIV while, rather importantly for drilling applications, reducing drag. High angles in the flex joints at either end of the drilling riser due to drag are limiting to operations. Helical strakes, while they are very simple, passive devices that quite effectively suppress VIV, increase steady drag. This "drag penalty" is not an issue for many other types of riser on which strakes have been employed successfully; however, drilling risers require an alternate solution of which fairings are but one example.

Both campaigns in which the drilling risers were fitted with fairings were relatively short in duration compared to the extensive lengths of time for which we have unsuppressed riser data. In addition, in one case, currents never reached significant enough levels for which VIV might be expected. But, in the other case, current speeds did reach a high enough level that VIV would have been expected for a riser without suppression. Figure 25 shows (in red) high current impinging on the faired section of the riser, however, in this case no VIV was measured. By contrast, for a time period during the same campaign in which an unsuppressed section of the riser encountered more moderate current (see Figure 25, green profile), detectable VIV did occur. Due to the sheer lack of data, these results cannot be considered conclusive. However, in a directional sense, at least, it appears that the fairings were effective in suppressing VIV. Further, on-board personnel reported that operations were never affected by either vibration or high flex-joint angles that may have been attributed to high drag.

Detailed performance data on these fairing designs are not available to the public, so a posteriori interpretation of monitoring campaigns like this one is the only way to discern their global performance. Taggart & Tognarelli [8] present some suppression and drag – reduction performance data from model tests of alternative, emerging fairing designs that may ultimately be used in predictive models.

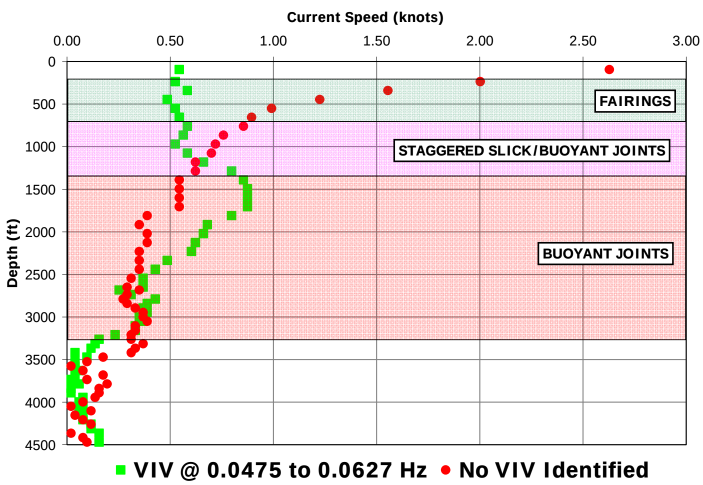

Figure 25 – Example Measured Current Profiles and Associated VIV Occurrence for 4,600ft Drilling Riser with Fairings

Fins. In yet another monitoring campaign, the drilling riser slick joints were fitted with Lankhorst fins or bumper bars. The purpose of these fins was to protect the auxiliary lines of the riser joints. However, it was determined via analysis and model tests that they could have a VIV-suppression effect.

This has been confirmed to some extent in the full scale data. Review of the measured VIV frequencies, current profiles and most likely power-in regions shows that when VIV occurs in this riser, the most likely power-in region is the continuous buoyancy region. To demonstrate this, a comparison of the field measured VIV frequency and that calculated using SHEAR7 with a Strouhal number of 0.20 is shown in Figure 26. The comparison is given for two cases:

1. Excitation is allowed in any part of the riser;
2. Possible excitation outside the continuous buoyancy region is turned off by setting the lift reduction factor to 0.0 in the fin joints and buoyant joints in the staggered region.

It can seen from this comparison that on average the calculated frequency exceeds the measured frequency for case 1 and is better matched with case 2. This indicates that the power-in region is not within the high current region with fins and staggered buoyant/finned joints but within the lower current continuous buoyancy.

Again, supporting data are limited and more are needed to establish certainty in the conclusions. However, indications to date are that the fins do indeed suppress VIV without introducing a significant drag penalty. If further substantiated, this would be a key finding as these fin devices can be fitted and stored with the riser joints. They do not need to be installed and removed during every riser deployment and retrieval cycle as a fairing device does. Hence, their use would save valuable time and associated expense compared to other suppression devices with the added benefit of riser protection during running and retrieval, for which the fins are designed.

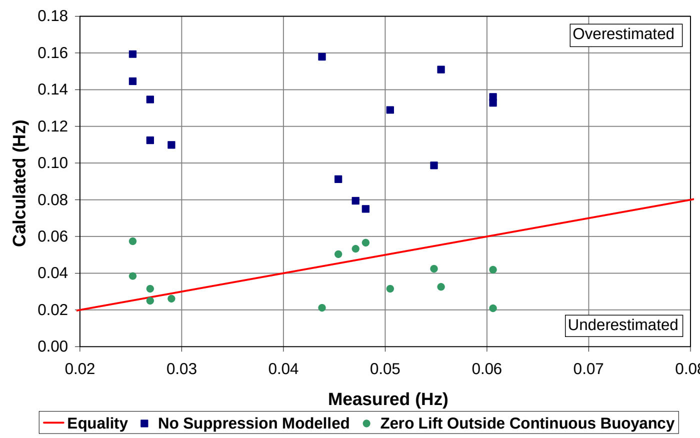

Figure 26 – Measured vs. Calculated Frequency for Different Power-in

CONCLUSIONS

By monitoring drilling risers in the field, BP has been able to ensure that they are being operated safely and prudently with a high factor of safety over the course of the monitoring period. This assurance is not so easily predicted or hindcast using the most common industry VIV analysis tools.

For full scale drilling risers without VIV suppression, data show that state-of-the-art analysis methods are, on average, inherently 30X conservative on a maximum fatigue damage basis. This average bias may be reduced by adjusting the maximum lift in the lift curve utilized in the method; however, the ability to do this is limited due to the significant scatter in measured fatigue damage due to VIV.

The scatter may come from several sources, among them: randomness in the environmental loading, namely the incident flow, or nonlinearity in the VIV phenomenon that is not captured in state-of-the-art analysis models.

Data collected do not reveal details regarding the stochastic nature of the environment, i.e., waves and currents – only the ten-minute average current profiles were measured. However, they do reveal some aspects of the riser response that are not captured in present techniques and, as such, are sources of inaccuracy. Thus, future work should include the investigation of whether alternative models that better represent the observed physics would produce more acceptable solutions in terms of both conservatism and prediction confidence.

The data also reveal that VIV does not occur nearly as often as it is predicted. One avenue of ongoing work is an investigation of the relationship between VIV probability of occurrence and current profile shape.

The field measurements have gone some way towards confirming the acceptability of connected drilling riser VIV response. However, higher harmonics during rig move and hang-off have been identified as a potential concern and it is recommended that these operations should be a key focus in future drilling riser monitoring programs.

Finally, from the limited data sets available, it appears that some presently available fairing designs are effective in suppressing VIV. However, limited understanding of these particular fairings' hydrodynamic performance likewise limits the ability to model them in existing or novel analysis codes. Until better insight is gained through, for example, model tests, the best way to assess fairing performance is to monitor drilling risers on which they have been installed.

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