Abstract

Throughout drilling, completion and workover activities risers are subject to environmental loading from currents, waves and vessel offset, these dynamics could cause fatigue in the riser structure. Due to their smaller diameter, completion and workover risers (CWORs) are especially susceptible to Vortex Induced Vibration (VIV) during open water operations.

An operator began development drilling on a field offshore Indonesia using a jackup rig in around 95m water depth. A 7-5/8” completion riser was used to complete the wells with a surface blowout preventer (BOP). Due to the nature of the application and the severity of the environmental loading conditions, VIV was observed during completion of the first well. Although riser analysis showed that currents over 1.5 knots were fatigue critical for the completion riser, two uncertainties remained in the model:

- The through depth current loading;
- Effectiveness of the riser vortex suppression.

Because of these unknowns and in order to demonstrate fitness-for-purpose of the completion riser during the well completion operations, a VIV monitoring system was installed. Providing the utmost simplicity, this monitoring system consisted of a single dynamic curvature sensor installed at the top of the riser, 3.5m below the drill floor. This sensor was connected to a central control unit via a topside cable. The strain data was captured and calibrated on board using proprietary software, with the bending stress data calculated at 8 points around the riser circumference.

This paper provides details on the monitoring system provided. On top of this, the paper will analyse the data collected throughout these completion operations and share the key conclusions from this monitoring campaign.

Introduction

Vortex Induced Vibration (VIV) is a common issue in current dominant environments for both shallow and deep water operations. An operator was developing a gas field located offshore Indonesia, planning for exploration and appraisal wells. The metocean study found that high current speeds of up to 1.5m/s (2.9 knots) were recorded in the region. In addition, the measured data included a large Soliton event at the surrounding area. Due to the harsh environmental conditions combined with the slender size of the completion riser, VIV was a concern. A preliminary VIV analysis on the drilling and completion riser had been conducted to assess the fatigue performance when subjected to the harsh environment. Appropriate recommendations were highlighted including the use of VIV suppression devices on the completion riser to extend the fatigue life during the operation. A modest VIV suppression system was proposed, using a wire rope strapped along the riser body. However, due to the uncertainty of the through depth current loading and vortex suppression efficiency, riser VIV monitoring was considered during the operation. The objective of the monitoring system was to identify and measure the riser strain and vibration in real time and to quantify the fatigue
stresses during completion and workover (CWOR) operations. This paper will initially discuss the technology used for riser strain monitoring, before detailing a case study on this specific application. The case study includes the data from the monitoring campaign conducted followed by discussion and recommendation.

Riser Strain Monitoring

In order to understand the fatigue caused by metocean factors and to estimate remaining life of the riser, monitoring systems are often required. Even in shallow water, riser length means that motion sensors are often used for these applications. Motion data loggers, using a combination of three axis acceleration and two axis angular rate sensors, are installed at strategic locations along the riser (Diestler et al, 2014). Using a placement strategy based on preliminary analysis, these motion loggers do not have to be located along the entire length of the riser. Instead, a strategic clustering of loggers at one or both ends of the riser can still allow prediction of global riser response with the required accuracy (Podskarbi and Walters, 2006).

However, although the global response data delivered by motion sensors make them the most popular approach to riser monitoring applications, strain gauges can also be used to measure local bending and curvature. The localised nature of strain measurement systems means that they are usually installed alongside motion sensors. Where riser analysis shows a particular area of concern, however, strain sensors can be used on their own to capture detailed strain response of fatigue critical areas. Location factors can be used in the analysis to predict fatigue along the entire riser. Strain gauges have been used for this purpose for many years in the offshore industry, with countless applications installed on a wide range of riser types. However, although strain gauging remains an important technology for riser monitoring systems, there are certain downsides to using this approach:

- Installation time: installation of strain gauges is a complex process requiring modification of the riser itself, by removal of its coating. Installation can take between 5 and 10 days, depending on scope and installation location;
- Retrievalability: although strain gauge sensors can be replaced with the riser on deck, the installation time for replacement can be problematic;
- Sensor calibration: although calibration of the strain gauge can be performed, it must be planned in advance. This approach is thus not suitable for situations where a quick turnaround is required.

Alternatively, retrofit strain sensors can be used. These provide the same data as strain gauges but without the disadvantages stated above. This paper discusses one such sensor, a field proven dynamic curvature sensor which offers a simple approach to riser monitoring.

The dynamic curvature sensor is a unique, patent protected, strain sensor specifically suited for riser fatigue monitoring where the response is dynamic bending dominated. The sensor is sealed, oil-filled and pressure balanced allowing installation at depths up to 3000m. The sensor measures 19mm outer diameter and 0.5m in length and it is attached to the outside surface of a riser. It changes in sympathy with the riser pipe and measures the change in riser curvature in 2 planes allowing local dynamic bending stress to be determined and fatigue damage rate to be calculated.

Table 1 shows a selection of sensor specifications. The dynamic curvature sensor has a less than 2 micro-strain resolution, making it sensitive enough to capture accurate fatigue data in even the calmest sea states. This capability is essential for measuring response under day to day current profiles and waves that contribute significantly to damage accumulation.

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
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<tbody>
<tr>
<td>Strain Resolution</td>
<td>&lt;2 µstrain RMS (for pipes between 6” to 12”)</td>
</tr>
<tr>
<td>Strain Accuracy</td>
<td>±6% of riser strain on the surface (for pipes between 6” to 12”)</td>
</tr>
<tr>
<td>Temperature range</td>
<td>-5°C to 80°C (storage) 0°C to 65°C (operation)</td>
</tr>
<tr>
<td>Design pressure</td>
<td>3000 meters water depth</td>
</tr>
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Table 1 - Dynamic curvature sensor specifications
The dynamic curvature sensor has a number of advantages over the use of traditional strain gauges:

- **Installation**: unlike strain gauges, the strain sensor can be installed by a single engineer in under an hour, making it ideal for projects where quick turnaround is required. The sensor is attached to the riser via four machined blocks made from titanium. These blocks are strapped to the riser (see Figure 1);
- **Retrievability**: whilst strain gauges are a challenge to replace, the dynamic curvature sensor can be retrieved and used on future projects. This makes the sensor ideal for short projects. For longer projects this allows retrieval of the sensor for repair, maintenance and recalibration;
- **Sensor calibration**: being an off-the-shelf, standard product means that the sensor has already been calibrated prior to installation.

![Figure 1 – Method used to strap the strain sensor to a pipe](image)

In house qualification of the dynamic curvature sensor has been carried out on 6” and 11.75” pipes, with a consistent and linear calibration factor achieved between the two diameters. The sensor has also been used on various drilling risers with diameters up to 24”. For these applications, qualification was carried out using field data rather than laboratory data.

During the verification programme, a dynamic curvature sensor was attached to the sample pipe using the standard deployment method shown in Figure 1. A reference strain gauge package (made up of foil type strain gauges installed in the orthogonal orientation along the circumference of the sample pipe) was installed to measure strain on the sample pipe surface. A calibration was first carried out to derive the strapping factor (SF) for the sensor. By utilising this factor, the measured sensor curvature can be converted into the curvature of the sample pipe. These measurements are then compared with those measured by the reference strain gauges in the verification programme.

After the strapping factor (SF) is derived, the sensor curvature is converted into the curvature of the sample pipe. The relative error between the curvature measured by the dynamic curvature sensor and the strain gauge should be within ±6%. This must be true for both static and cyclic loading.

Figure 2 shows an example of the results on the 11.75” pipe. ±6% error bands are displayed using two dotted red lines symmetrically plotted around the 45 degree line. The pipe curvatures derived are plotted as dots on the graph for the five orientations (0°, 45°, 90°, 135° and 180°). As can be seen, all curvature data lies between the ±6% error bands.
A cyclic loading verification was also carried out. Again, sensor curvature is converted into pipe curvature using the SF factor obtained and compared with pipe curvature measured by the reference strain gauges. Tests were carried out at two frequencies, 0.3 Hz and 0.6 Hz. Figure 3 below shows the results from one of these tests.

Figure 2 - Pipe curvature comparison for all pipe orientations for 11.75 inch OD pipe

Figure 3 - Comparison of pipe curvature measured by dynamic curvature sensor and reference strain gauges with a pipe orientation of 0 degree with an oscillation frequency of 0.3 Hz
Case Study: Completion Riser Monitoring

Background

This case study will present a method for in-service fatigue monitoring of a completion riser run from a jackup MODU. The operator was developing the gas field located offshore Indonesia in a water depth of about 95m, using a jackup rig. A large diameter high pressure drilling riser was used to drill the wells with a surface BOP with a 7-5/8 inch completion riser used to complete the wells. A recommendation was made from the preliminary analysis report to implement workable solutions to mitigate riser strength and fatigue issues. One of the main concerns highlighted was the expected low VIV fatigue life on the riser during a high current speed event. Furthermore, the operator was planning to complete a number of wells for their second campaign meaning VIV was a major concern.

Due to the nature of the application and severity of the environment loading conditions, VIV was observed during the first well completion operation. It was also found that the recorded current speed during the first campaign was continuously exceeding 1.1m/s (2.0 knots). A riser fatigue monitoring system was suggested to assist the next planned completion operation. The system was required to record and measure riser response behaviour. Preliminary VIV analysis showed that current speeds in excess of 0.8m/s (1.5 knots) were observed to be fatigue critical for the 7-5/8 inch riser. Furthermore, it was recommended to install a modest VIV suppression device, using a marine rope wrapped along the riser. A picture is shown in Figure 4.

![Figure 4 – Marine rope strapped along the riser body for VIV suppression](image)

An example of the completion riser space-out provided by the operator is shown in Figure 6. The submerged portion consisting of the 7-5/8 inch riser extends from the subsea completion tree to the rig floor. The riser strakes (as shown in Figure 4) are installed along the riser section that is exposed to the water column. An example of fatigue life plots along the riser from the global riser analysis is shown in Figure 5. The highest fatigue damage is expected at the riser joint just below the rig floor and at the tree running tool adaptor connection. This is expected since high fatigue loads are usually generated in the areas where support exists. However, the fatigue plot shown suggests that the threaded connection of the 7-5/8 inch connector is also subjected to excessive fatigue damage making the whole riser system an area of concern. Since no details of the connector thread are available, an assumption is made assuming SCF 2.0 with DNV fatigue details of B1. This considers standard SCF expected for a threaded connector.
The monitoring system was designed based on both client requirements and operational considerations. The main factors that were considered during system specification were:

- **Riser analysis:** the riser analysis identified fatigue critical locations along the riser. Maximum bending was shown to be at the top and bottom of the riser, making these the key areas of concern (Figure 5);
- **Data requirement:** the operator did not require the software to perform real time data processing. Instead, data would be sent for post processing on-shore, with reports delivered to the operator every hour;
- **Operational considerations:** due to the high current speeds there were concerns over using an ROV for subsea sensor installation and retrieval. In addition, rope access to the top section of the riser was not possible since the riser was flowing with gas.

The operator required information on overall fatigue capacity of the riser system to enable safe and efficient operational decision making. For this project, a very simple retrofit monitoring system was installed. This system consisted of a single dynamic curvature sensor installed 3.5m below the drill floor and a central control unit located in the driller’s cabin to collect and display data. A 76m cable was run underneath the drill floor to the driller’s cabin, allowing data transfer from the sensor to the control unit. Due to it being installed in a hazardous area, all equipment was required to be explosion proof. The monitoring system provided utmost simplicity whilst meeting the requirements of the operator. Figure 6 shows a schematic of the installed monitoring system.

The dynamic curvature sensor was installed on the 7-5/8 inch riser near the drill floor during the well test operation. The device was strapped to the riser body using aluminium strapped tools at the elevation shown in Figure 6. The sensor was connected to the central control unit located at the driller’s cabin via an explosion proof umbilical, allowing for real-time measurement. Cable routing and installation was done according to both rig and supplier procedure, resulting in a safe and efficient installation. The data was read and stored in a laptop pre-installed with proprietary monitoring software. A software screenshot from this project is shown in Figure 7.
7-5/8" Completion Riser System Stack Up

Lubricator
Test Tree
Drill floor=123.70m
Btm of Rotary Beam
Pup Joints, 7.625"OD and 6.875" ID, Grade L80

Derricks Cabin

3.5m
Dynamic Curvature Sensor

Sea level=95.1m

Riser Joints, 42ft, 7.625"OD and 6.875" ID, Grade L80

Strakes Coverage

Tree Running Tool
SS Tree
Wellhead 30'/18-3/4"

Conductor, 30" OD and 27" ID, Grade X52

Point of fixity

6.70m
Seabed=0

60.00m

Figure 6 - Location of dynamic curvature sensor on riser

Figure 7 – Software front screenshot from rig
The strain sensor measured the change in riser curvature in real time, with the data also available to be downloaded for fatigue calculation post processing. The strain sensor was calibrated to record continuously at a frequency of 10 Hz during the well test operation. The well test was conducted over 3 days, with the riser pipe strain values displayed and monitored in the driller’s cabin on a real time basis. The logging data is then post-processed every hour to calculate the riser fatigue damage consumption, with results reported to the operator every 1 hour. The calculation of the fatigue damage assumed that the 7-5/8 inch riser was a new riser joint. The current speed is also measured throughout the well test campaign. The primary purpose of the current measurement was to confirm the relation of riser fatigue response to the current speed. An example weather report defining wind, wave and current data is shown in Figure 8.

The strain data was downloaded and calibrated on board using a proprietary post processing software. The stress and bending time traces recorded in 2 vertical planes were used to calculate the stresses at eight points around the pipe circumference. The riser plane and pipe circumference is shown in Figure 9. The stress time traces calculated at eight points circumferential are converted to a stress histogram using Rainflow cycle counting using an in-house software program. The fatigue damage is calculated at the measured location based on the riser pipe properties. A location factor was used to extrapolate the fatigue damage to critical locations along the riser system where peak damage occurs. The location factor is defined as the ratio of the fatigue damage between the peak riser fatigue location from the global riser analysis and the measurement location.

Riser Fatigue Monitoring Result

The fatigue measurement for the 7-5/8 inch riser was successfully completed during the length of the first well test campaign. The fatigue damage rate was calculated for eight reference points of the pipe circumference for each recorded data. A plot of fatigue damage rate over the logging period is shown in Figure 10. A conversion to obtain the actual fatigue damage accumulated over a 1 hour logging period can be found in the formula below. The
accumulated fatigue damage is defined as the consumed fatigue life at the respective location for every one hour. An example of accumulated fatigue damage contribution in percentage (%) over the monitoring campaign is shown in Figure 11. It is found that the fatigue damage consumption was less than 1% at the end of the campaign and is considered negligible. It is believed this is due to the low current speed during the campaign. The average recorded current speed during the well test campaign is found below 0.5m/s (0.9 knots) and maximum current speed is 0.8m/s (1.6 knots). This is in line with the findings from the predicted riser VIV analysis conducted earlier.

\[
\text{Fatigue Damage (Hourly)} = \text{Damage} \times \left( \frac{3600 \text{ sec}}{365 \text{ days} \times 24 \text{ hours} \times 3600 \text{ sec}} \right)
\]

\( (1) \)

Figure 10 – Fatigue damage rate at 8 circumference point of the 7-5/8 inch riser

Figure 11 – Maximum cumulative fatigue damage against recorded current speed
Potential Improvements

Some areas of improvement are found during the monitoring campaign. The recorded current speed was only available for surface current speed located 3-5m below the water surface. As the current profile was unknown and the existence of Soliton phenomenon in the surrounding area was found during the earlier metocean study, through depth current monitoring during the operation will benefit the study to help relate the riser fatigue response against the current profiles. This will also help predict the expected riser response for future planned well completion operations in the surrounding area.

The riser monitoring was only conducted for two days during the well test campaign. It is recommended to have a longer monitoring campaign in order to increase the probability of capturing riser response during high current speed events.

Conclusion

Due to their small diameter, completion and workover risers are particularly susceptible to VIV. This can lead to excessive fatigue loading at critical locations along the riser. To mitigate this, riser monitoring systems can be installed to provide real time fatigue data to personnel on the rig.

This paper has described a monitoring campaign during completion operations offshore Indonesia using a jackup MODU. The operator decided to implement the integrity monitoring system after witnessing VIV during operations. The global riser analysis was used to determine the locations of fatigue hotspots along the riser.

The monitoring system provided utmost simplicity whilst still meeting the requirements of the operator. The system was based around a single dynamic curvature sensor installed on the upper section of the riser. This dynamic curvature sensor is a unique, patented protected, strain sensor specifically suited for riser fatigue monitoring. The sensor provides three primary advantages over the use of traditional strain gauging:

- Rapid installation;
- Simple to retrieve and redeploy;
- Sensor qualification before installation.

Strain data was displayed in real time on the rig and was also downloaded every hour for fatigue calculation post processing. The monitoring campaign found that the fatigue damage consumption was less than 1% at the end of operations, considered negligible. This campaign showed the operator that completion activities had been conducted in a safe manner and the information can be used to optimize the remaining development operations.

References