Mitigation of Wellhead and Conductor Fatigue Using Structural Monitoring

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ABSTRACT
Wellhead and conductor fatigue loading is becoming an increasingly important issue in offshore drilling operations. A move towards higher pressure and higher temperature wells, deeper water and increasingly inhospitable environments has led to a substantial increase in the weight and size of offshore equipment. This, combined with dynamic loading from the environmental forces acting on the vessel and riser, has greatly increased the loads that subsea wells are exposed to. Over the past few years this has increased the potential for severe fatigue loading in the wellhead and conductor system.

This paper highlights the major factors driving fatigue loading in the wellhead and conductor system, including environmental factors as well as those resulting from the use of larger 5th and 6th generation rigs for offshore drilling activities. The options available to mitigate these fatigue issues are also discussed, such as improvements at the design and planning stages of the operation.

Particular focus is given to the growing use of structural monitoring in order to more accurately assess loading in the wellhead and conductor system and thus reduce the inherent conservatism present in fatigue analysis. By allowing the calculation of actual fatigue damage throughout a drilling campaign, monitoring can provide critical data for ensuring the structural integrity of the subsea well.

INTRODUCTION
Typical offshore drilling operations are carried out using drilling risers and subsea BOP stacks deployed from mobile offshore drilling units (MODUs). A typical riser stack up is shown in Figure 1. A riser is needed in order to establish access to the well from the MODU. The first stage of drilling operations (installing the wellhead and conductor system) is carried out in open sea. Once the wellhead is installed the marine riser and BOP are connected, with all further drilling and completion operations taking place within the marine riser. The wellhead and conductor system forms the connection point between the riser system and the well and is a key load-bearing structure which supports the BOP, LMRP and Christmas Tree at various times throughout the life of the well. As well as this the system also forms the structural foundation member of the well, supporting the various casings that link the hydrocarbon reserve to the seabed surface.

The wellhead and conductor system is subjected to cyclic lateral loads from the drilling riser. This means that as long as the riser is connected to the wellhead, dynamic loads will be transferred from the riser to the wellhead. These loads are generally driven by three factors [1]:

1
- Severe wave conditions can cause vessel motions which are subsequently transferred to the top of the drilling riser;
- Waves can subject a direct hydrodynamic load on the riser resulting in riser motion;
- Under strong, steady currents the vortex shedding at the leeward side of the pipe may lock-on to the natural frequencies of vibration of the riser system, a phenomenon known as vortex-induced vibration (VIV);

![Diagram of drilling rig components](image)

**Figure 1- A typical drilling riser stack up deployed from a MODU**
The service life of a well is typically around 20 years during which time there are a number of operations that require the wellhead to connect directly to some sort of vessel via a riser system. These operations include drilling, completion, workover/ intervention and abandonment. The increasing complexity of well completions and the advancement of drilling operations into ever more severe environments have resulted in longer periods where a riser is connected to the well.

![Diagram of wellhead and conductor system showing key fatigue hotspots](image)

**Figure 2:** A typical wellhead and conductor system showing key fatigue hotspots[3]

The dynamic loads imposed on the system by the response of the MODU and riser generate elastic stress cycles in the wellhead and upper portion of the conductor [2]. The exposure of the wellhead and conductor to these loads over an extended period could lead to allowable damage in the wellhead and conductor being used up too quickly. Fatigue damage generally accumulates at certain critical points (known as fatigue hotspots) which include certain welds and connectors from the base of the wellhead housing to a depth of 10-15m below the mudline (see Figure 2).
DRIVERS OF WELLHEAD & CONDUCTOR FATIGUE PERFORMANCE

VIV

VIV generally becomes the governing environmental load on drilling risers in water depths exceeding 250 metres. VIV occurs when the frequency of the vortices shed by current flow around the riser matches a natural frequency of the system, resulting in amplified lateral motions (resonance) of the riser. These high amplitude movements in the riser system can lead to accelerated fatigue and system degeneration. VIV can cause fatigue damage to both the riser and the wellhead and the effect that this has will be determined by factors including the hydrodynamic properties of the riser and the environmental conditions during the length of operations. Because of the potential fatigue damage it can cause, VIV is often seen as a limiting factor during drilling operations, causing operators to suspend drilling activity until the current speed reduces and lock-on ceases.

5th and 6th Generation Vessels

During offshore operations there are a number of parameters that influence the response of the drilling system. These include the riser, flexjoints, vessel design and BOP stack size. The movement of offshore oil and gas exploration into deeper waters and increasingly inhospitable environments has seen major changes to equipment in relation to subsea facilities. This has seen both the equipment on the seabed as well as the facilities for drilling and intervention increase substantially in both weight and size. For this reason the new 5th and 6th generation vessels differ in a number of ways from the older 3rd and 4th generation vessels:

- Riser system design- joints must be designed to cope with higher system tensions as well as greater hydrostatic pressures [3]. This requires an increase in the wall thickness of the riser joints as well as riser weight and stiffness;

- BOP stack size- BOP stacks for 5th and 6th generation rigs can be over 1.5x taller and almost 3x heavier than those on older 3rd and 4th generation vessels (see Table 1);

<table>
<thead>
<tr>
<th>Vessel</th>
<th>BOP Stack Height (ft, m)</th>
<th>BOP Stack Weight in Air (kips, Te)</th>
<th>BOP Period Stack (s)</th>
<th>Natural</th>
</tr>
</thead>
<tbody>
<tr>
<td>3rd Generation Vessel</td>
<td>33.0, 10.1</td>
<td>338.7, 153.6</td>
<td>4.4</td>
<td></td>
</tr>
<tr>
<td>4th Generation Vessel</td>
<td>46.2, 14.1</td>
<td>411.7, 186.7</td>
<td>5.3</td>
<td></td>
</tr>
<tr>
<td>6th Generation Vessel</td>
<td>53.3, 16.3</td>
<td>639.6, 290.1</td>
<td>6.4</td>
<td></td>
</tr>
</tbody>
</table>

Table 1- Comparison of BOP stack properties

The increased size of subsea equipment can impart greater loading into the wellhead and conductor system in two ways, particularly of concern in shallow to moderate water depths (100m – 500m):

- The lever arm effect associated with motion of the riser and BOP stack above the wellhead is exacerbated leading to larger bending moments at the wellhead and conductor for the same lateral displacement of the riser and BOP;

- Resonance of the BOP stack under wave loading is more likely as the natural period of the BOP stack is increased and brought closer to the typical range of wave periods (around 5-8 seconds);

The combination of these factors can cause fatigue damage from 6th generation BOPs to be as much as 17x higher than from those used on 3rd and 4th generation vessels [4]
Soil Strength

Soft soil gives greatly reduced lateral support to the wellhead and conductor system. In these conditions the magnitude of the bending loads are larger as greater deflections of the BOP stack can occur, resulting in further reductions in fatigue life. The peak bending moment in soft soils typically occurs 5 to 10m below the mudline putting the conductor and surface casing most at risk of fatigue loading. In stiff soils peak bending loads tend to occur between 0 and 5m, putting the welds and connectors near the mudline at greatest risk of fatigue accumulation [1] (see Figure 3).

Figure 3- Impact of soft soils on conductor and casing fatigue life [1]

MITIGATION MEASURES

Design Enhancements

In order to ensure that the wellhead and conductor system is suitably robust, it is necessary to consider the design enhancements which can be reasonably implemented to improve fatigue capacity:

- Locating critical welds and connectors away from regions of high bending loads wherever possible;
- Increasing the diameter or wall thickness of the conductor if the associated increased manufacturing and transportation costs are manageable;
- Use of a rigid lockdown wellhead can also improve fatigue life at the HP housing weld and casing connectors by up to a factor of 10 [1];
- Improve the quality of wellhead housing welds through rigorous post-weld non-destructive testing (NDT) and machining [3];
**Operation Planning**

Seasonal fatigue assessments have shown that, in regions that exhibit variability between seasons, fatigue damage rates resulting from drilling operations can fluctuate significantly depending on the time of year. While operational flexibility is desired by operators, wellhead and conductor fatigue life can be maximised by avoiding operations in the most undesirable environmental conditions [3].

Another way to improve fatigue performance is to use a vessel with better motion characteristics and a smaller BOP, especially in shallow to moderate water depths. 5th and 6th generation vessels may offer more robust operational capabilities in deep water but as described above they can harm fatigue performance of the wellhead in shallower waters. However, when selecting a rig the impact on permanent infrastructure is only one of a number of commercial and technical considerations that must be taken into account. Rig availability, station keeping requirements and operational requirements must also be considered and may drive an operator to select a deepwater 5th or 6th generation rig for shallow water activities.

**WELLHEAD FATIGUE ANALYSIS**

In order to evaluate the fatigue performance of the wellhead and conductor system a series of fatigue analyses are performed. Wellhead fatigue analysis is a complex and multi-disciplinary process, requiring a combination of structural, hydrodynamic, geotechnical, metocean and operational knowledge.

The use of accurate data is essential when assessing whether a wellhead and conductor system has the required fatigue capacity for a proposed operation. If the data is not accurate or, as is more common, not available, then assumptions must be made. Because of the extreme risk elements that must be factored in, these assumptions can result in highly conservative models leading to significant over-predictions of fatigue damage. This is particularly evident in frontier regions where existing knowledge of environmental conditions and seabed properties is limited [3].

A grey area thus exists as to how operators should act on the results of analysis. Although the well documented conservatisms allow the numbers to be taken with a pinch of salt, a lack of infield experience and relative comparisons means there is often no basis for removing the conservatism. The biggest issue for operators revolves around how to qualify this lack of confidence with analysis.

**STRUCTURAL MONITORING**

A further option for operators, and one that is becoming increasingly popular during drilling operations, is to monitor physical parameters such as strain, acceleration and angular rate to determine the actual fatigue accumulation experienced by the wellhead and conductor system.

Monitoring fatigue accumulation in wellhead and conductor systems can involve inputs from a number of sensor types which can be located at various points on the vessel, along the riser or on the BOP/ LMRP stack. Figure 4 shows some of the typical areas which can be instrumented as part of a wellhead and conductor fatigue monitoring system.

There are generally two reasons that drive operators to introduce systems to monitor fatigue performance during drilling:
• To allow comparisons between the actual and predicted parameters. Measured bending, stresses, tensions and motions can be compared to the analysis to remove some conservatism and improve overall understanding of system behaviour;

• To improve confidence during drilling operations. Monitoring systems can show how much fatigue damage has been accrued during a drilling operation, reassuring operators that their equipment remains within the allowable or ‘safe’ fatigue limit;

Figure 5 shows a comparison between monitored and predicted fatigue over a one month period. This type of comparison helps the operator to improve their understanding of the fatigue performance of their wellhead and conductor in various environmental states, and provides justification should they want to operate outside the limits defined by the analysis.

![Cumulative Fatigue Damage Graph](image)

**Figure 5- Comparison between measured and predicted fatigue damage**

The measured data is processed in order to determine the cause of motions, and also calculate the fatigue damage to the wellhead and conductor. The data can improve operational decision making by supplying the operator with the required information. This can be used as guidance on when to disconnect from the well in extreme conditions, as well as optimising riser tension to reduce the risk of VIV.

The measured data also allows for analysis models to be refined by comparing the actual measurements to the calculated results. Calibrating analysis models with historical data helps improve predictions for future operations by reducing conservatism caused by uncertainties.
Figure 4- Typical regions assessed to determine wellhead and conductor fatigue.
Online Fatigue Monitoring

An increasing focus on wellhead and conductor fatigue is driving operators to seek greater volumes of data on the state of their subsea assets. This has been reflected by a growing demand for online (hardwired) monitoring systems. These systems supply real-time data to the rig, allowing operators to view and analyse the information immediately. This information can therefore be used as an input to operational planning.

Due to the various influences on wellhead and conductor fatigue loading a robust monitoring system might involve a wide range of sensors deployed in a variety of locations:

- **Environmental:** Acoustic Doppler current profilers (ADCPs) can be used to measure current speed and direction through depth. These can be mounted either topside on the platform keel or subsea on the seabed.

  Wave height and period can be measured by air-gap wave radar sensors. These calculate the distance between the water surface and the sensor to calculate wave height. Installing several wave radars on opposite sides of the vessel can allow wave direction to be calculated, as well as providing redundancy in case of sensor malfunctions.

- **Motion:** Subsea data loggers incorporating accelerometers and gyroscopes can be used to measure motion along the length of the riser. This system allows the operator to observe whether the vibration pattern is steady and if it is approaching the riser’s self resonant frequency, helping to detect the presence of VIV.

  Motion data loggers can also be fitted with inclinometers and installed on the upper and lower flex joints to measure joint angle. Typically during drilling operations mean flex joint angle should be limited to 1-2 degrees in order to minimise potential wear issues that may arise from drilling riser rotation.

  Monitoring the BOP/ LMRP stack is required to establish the fatigue induced on the wellhead and conductor system. Limited access to the wellhead during drilling operations makes it virtually impossible to install monitoring equipment on the wellhead or conductor. Mounting sensors on the BOP/ LMRP is therefore the only practical method of measuring motion and vibration of the wellhead.
• Strain: Whereas motion monitoring requires fatigue to be inferred from the observed motions, strain measurements can be used to calculate fatigue with very little data processing.

Strain gauges can be used to calculate absolute strain, however problems related to installation time and subsea reliability mean they are not a popular option on drilling risers, particularly once drilling operations have already commenced.

Whereas strain gauges might take up to 5 days to prepare and install, dynamic curvature sensors can be installed in a matter of hours. These sensors calculate strain in the riser system by measuring the bending response of the riser. Although these sensors have greater reliability (especially subsea), there are potential accuracy issues in converting between the sensor curvature and the pipe curvature and using this data to infer strain.

• Software: The measured data is useless unless it can be converted into information that can support day to day as well as long term decision making. Specially designed software collects and analyses the data from the sensors and a local display on the vessel can show measured performance in relation to pre-defined KPIs. Real time data can be communicated with shore based management to help with high level decision making and may also be stored locally to allow for further analysis and aid with the future calibration of wellhead fatigue models.

Common Problems

Despite their recent rise in popularity there are still a number of problems associated with online monitoring systems:

• Cost: Online monitoring systems are generally much more costly than comparative autonomous systems. Hardwired equipment can be as much as 50% more expensive than a standalone counterpart, with expensive subsea cabling also contributing to the cost. Installation can also take up to 4 times longer increasing the requirement for offshore technician time. The installation of the cable during the running of the riser can also add to operating costs by delaying riser deployment. However, although capex is higher for hardwired systems, opex can be considerably lower since offshore technician and ROV time is not required to retrieve the data loggers to collect data or change batteries. The cost difference therefore depends on water depth, number of subsea loggers and length of system deployment.
• Reliability: The reliability of a monitoring system is related to the number of its components and their individual reliability. Due to the requirement of cables and connectors, online systems are much more complex and have many more components than standalone and acoustic systems, making them inherently less reliable [5]. Historically cables have been a major cause for concern with a high possibility of damage or even failure during riser deployment and retrieval.

• Redundancy: Standalone systems are naturally redundant, with distributed systems limiting the consequences of failure of a single instrument. Redundancy is also less of an issue with these systems since they are easily repaired (by simply replacing the faulty components). On the other hand, hardwired systems require redundancy to be factored in at design level to ensure that a single point failure is not possible. This can become one of the major design and cost drivers in the case of hardwired systems [6].

• Lead times: The offshore drilling industry is characterized by short term visibility, often requiring suppliers to react quickly to the needs of operators (particularly in cases of reactive integrity management). Lead times for online systems tends to be longer than for autonomous systems due to a combination of component availability, software writing, design of system installation and getting rig contractor approval for cable deployment.

For these reasons autonomous (standalone) monitoring systems continue to remain popular with operators looking to calculate wellhead and conductor fatigue. Due to their increased reliability and track record subsea these systems can be used for redundancy even when an online system is preferred. The trade off, however, is with the speed of data return, with operators having to wait weeks or even months to get access to the data from standalone systems.

CONCLUSION

As offshore drilling activities continue to venture into ever deeper waters and increasingly extreme environments issues with wellhead and conductor fatigue continue to grow. Soft soils, bigger and heavier BOPs and sub-optimal design are some of the factors exacerbating the cyclic loading experienced by the wellhead and conductor as a result of riser motion.

Effective measures to mitigate fatigue can be implemented at the planning and design stages of operations. Selecting a rig with a smaller BOP, positioning critical conductor and casing connectors away from high bending regions and improving weld quality can all help to greatly improve the fatigue performance of the system. However, due to technical and financial constraints these measures can be overlooked by operators, leading to fatigue issues that may pose a threat to the integrity of the wellhead and conductor system.

Where fatigue life predictions are particularly low, structural monitoring can be used to help reduce the level of conservatism in the analysis model. Measuring the actual response of the drilling system during operations means accurate fatigue accumulation can be calculated. Removing some of the uncertainty helps to fine-tune the model and reduce the level of inherent conservatism in analysis for current and future operations.
NOMENCLATURE

6DOF  6 Degrees of Freedom
ADCP  Acoustic Doppler Current Profiler
BOP   Blow Out Preventer
Capex Capital Expenditure
DNV  Det Norske Veritas
HP   High Pressure
HPHT High Pressure and High Temperature
LFJ  Lower Flex Joint
LMRP Lower Marine Riser Package
LP   Low Pressure
MODU Mobile Offshore Drilling Unit
Opex Operating Expenditure
ROV  Remotely Operated Vehicle
VIV  Vortex Induced Vibration
WH  Wellhead

REFERENCES


