The Growing Use of Structural Monitoring as Part of Wellhead and Conductor Integrity Management

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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.

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 wellhead system.

INTRODUCTION

Subsea wellhead and conductor systems are subject to cyclic lateral loads from the connected drilling riser. The wellhead system is exposed to significant loads that are imparted into the well conductor from the environment loading of the vessel and the drilling riser system. A typical drilling riser stack-up is shown in Figure 1. The cyclic loads driving the wellhead systems include:

- Wave driven vessel surge and sway motions that are transferred to the drilling riser;
- Wave driven direct hydrodynamic loading on the riser;
- Vortex-induced vibration (VIV) of the drilling riser.

While the drilling riser is connected to the wellhead system, these dynamic loads are transferred from the drilling riser to the wellhead system. Excessive fatigue accumulation may lead to the failure of the wellhead systems [1]. 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).

Offshore drilling operations have been completed successfully for several decades. However, industry is pushing the envelopes with deeper water depths, harsher environment, updated regulatory requirements, increasing size of BOP stacks with the 5th and 6th generation drilling rigs and increasing complex completions. As a result, conventional wellhead systems are frequently found to show poor fatigue response in analytical predictions based on the conservative input data. Therefore, an additional method of increasing confidence in analytical predictions and managing integrity of the wellhead system is required. Structural monitoring is a key enabling technology to provide on-going wellhead and conductor integrity assurance.

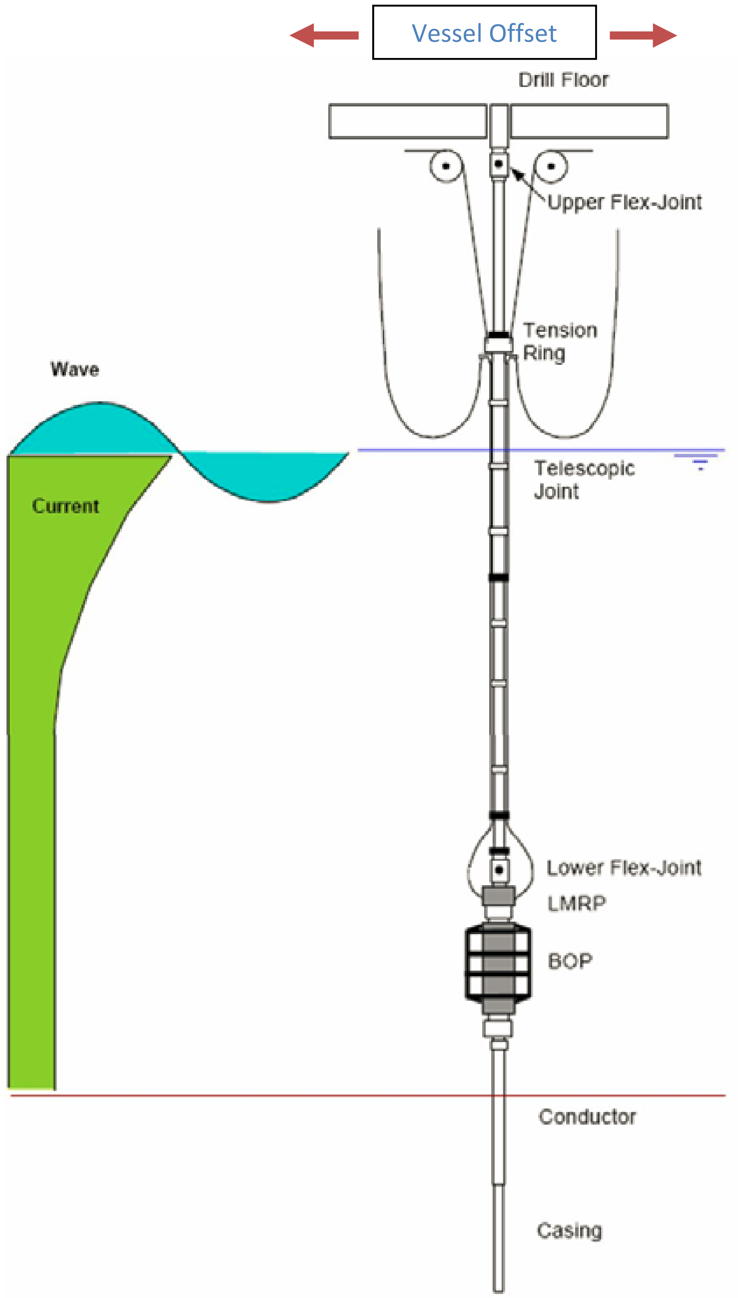

Figure 1 – *Typical Drilling Riser Stackup and Sources of Motion* [1]

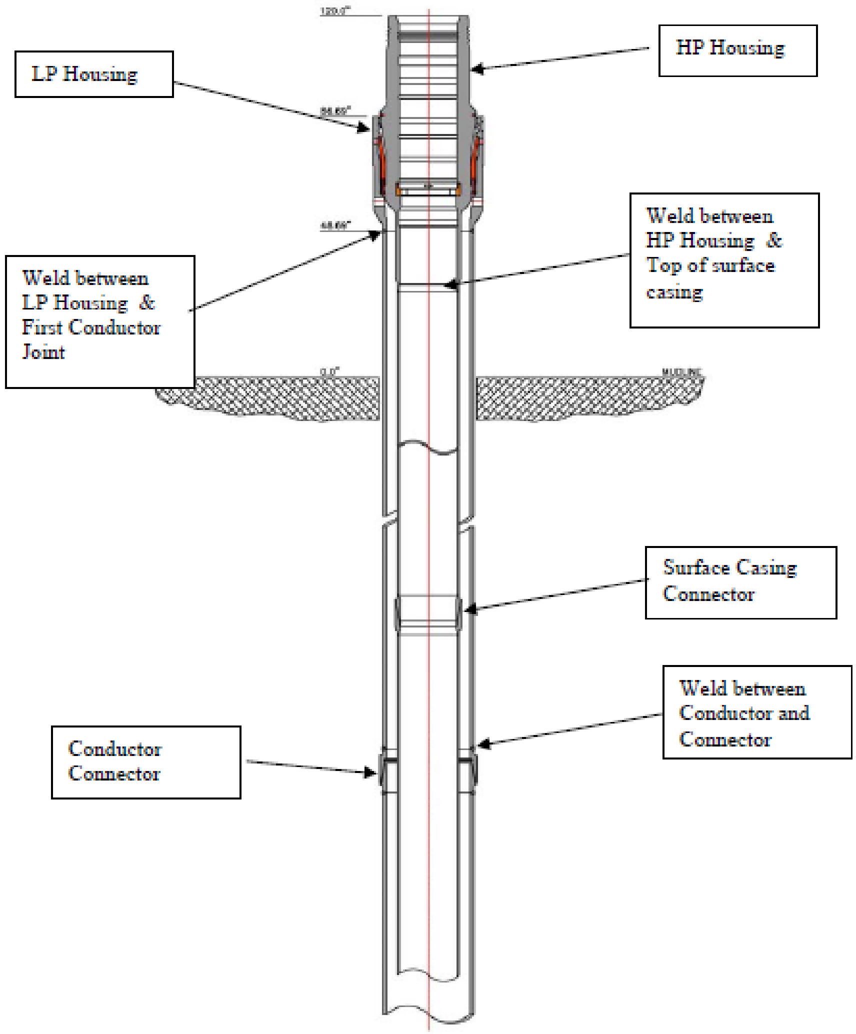

Figure 2- A *Typical Wellhead and Conductor System Showing Fatigue Hotspots [3]*

DRIVERS OF WELLHEAD & CONDUCTOR FATIGUE PERFORMANCE

Vortex Induced Vibration (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.

5^{th} and 6^{th} 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 5^{th} and 6^{th} generation vessels differ in a number of ways from the older 3^{rd} and 4^{th} 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 5^{th} and 6^{th} generation rigs can be over 1.5x taller and almost 3x heavier than those on older 3^{rd} and 4^{th} generation vessels as shown in Table 1.

Vessel	BOP Stack Height [ft, m]	BOP Stack Weight in Air (kips, Te)	BOP Stack Natural Period (s)
3rd Generation	33.0, 10.1	338.7, 153.6	4.4
4th Generation	46.2, 14.1	411.7, 186.7	5.3
6th Generation	53.3, 16.3	639.6, 290.1	6.4

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).

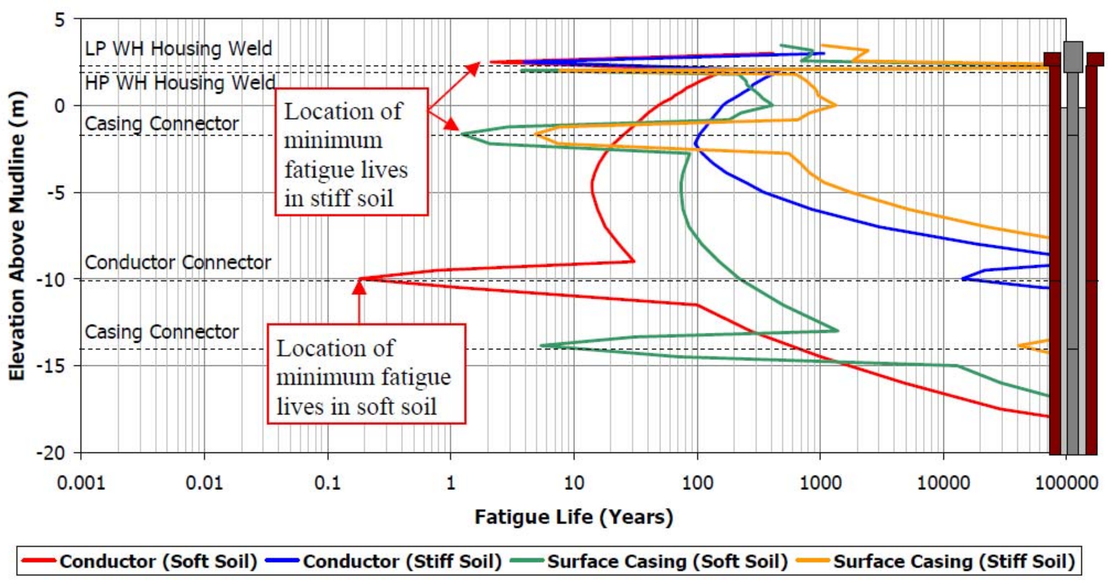

Figure 3 - *Impact of Soft Soils on Conductor and Casing Fatigue Life [1]*

WELLHEAD FATIGUE ANALYSIS

In order to evaluate the fatigue performance of the wellhead and conductor system a series of fatigue analyses are typically 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. While the analysis results are believed to be conservative, 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. This is where structural monitoring can provide invaluable information.

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, inclination 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;

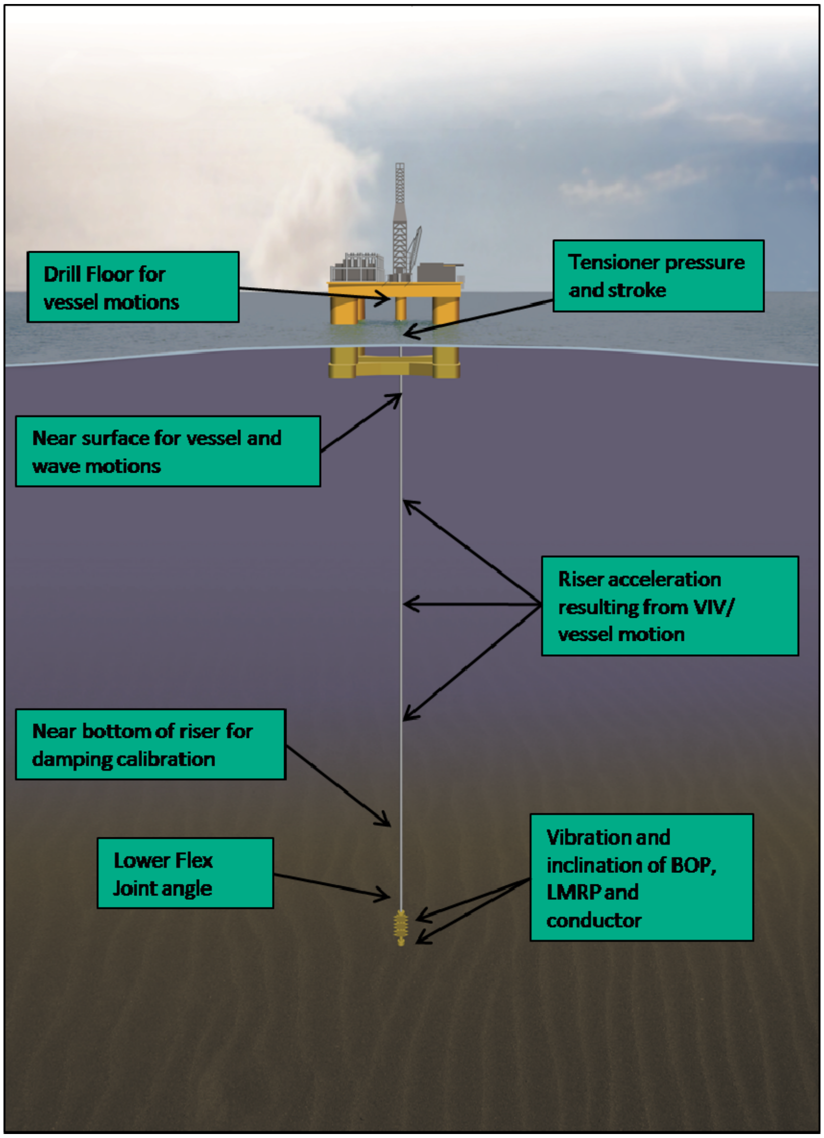

Figure 4 - *Typical Regions Assessed to Determine Wellhead and Conductor Fatigue*

Figure 5 shows an example 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

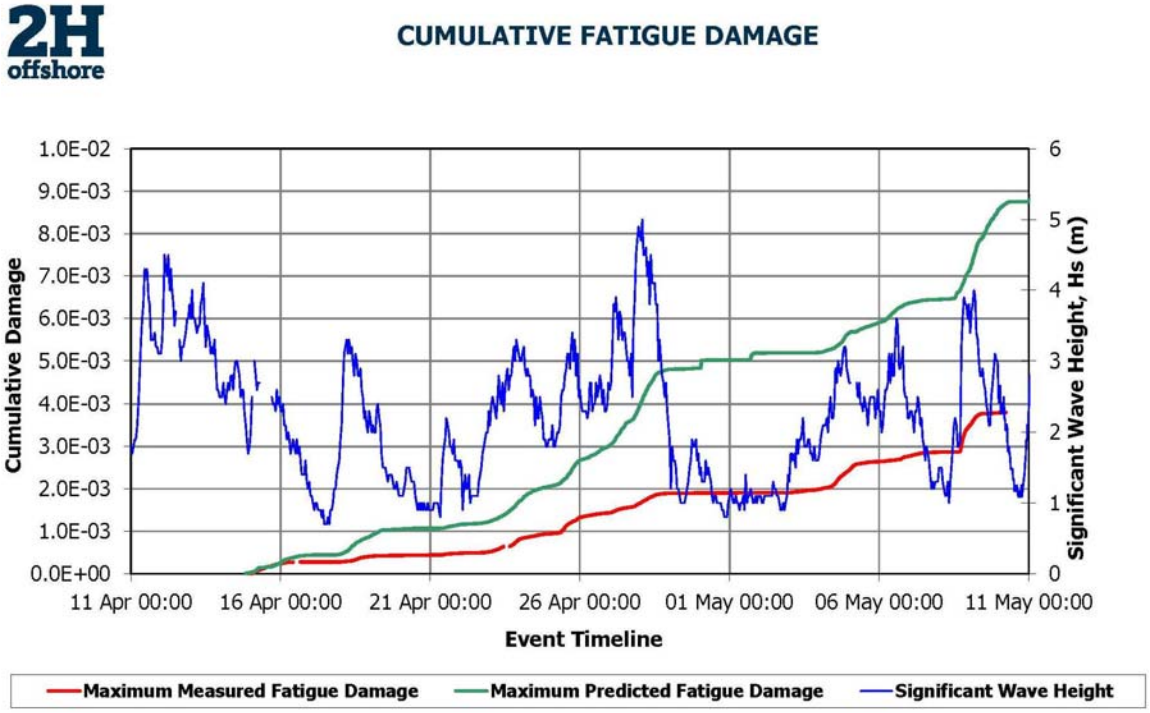

Figure 5- *Comparison between measured and predicted fatigue damage*

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.

Structural Fatigue Monitoring

An increasing focus on wellhead and conductor fatigue is driving operators to seek greater confidence on the state of their subsea assets. This has been reflected by a growing demand for structural monitoring systems. These systems can vary widely from vessel to vessel and may involve a number of various sensor system installed on the vessel, riser, wellhead and conductor system. The monitoring system design and configuration and the data communication method and frequency are driven by the requirements of the operator’s asset integrity management strategy. It is increasingly preferred to collect the data from surface and subsea sensors in real-time or quasi real time transferred to the rigs data acquisition system, allowing operators to view and analyse the gathered information immediately. This information can therefore be used as an input to active operational planning.

Most modern drilling Modus's are equipment with discrete sensor systems that may be fully integrated into the vessels control system. Due to the various influences on wellhead and conductor fatigue loading a robust monitoring system might involve a wide range of sensors the sensor systems found on most vessels are:

- DGPS Positioning System
- Tensioner pressure and stroke sensors
- Dynamic Position Systems (DPS)
- Wave radar (Wave height , direction and period)
- ADCP (Acoustic Doppler Current Profiler)

The output from these sensor systems may be invaluable for assessing the structural integrity of the wellhead and conductor due to vessel offset and environmental loading condition. The onboard sensor systems may be complimented by motion and or direct strain sensor systems deployed directly on the riser, wellhead and conductor area. Careful pre deployment consideration has to be given to the following criteria:

- Monitoring objective and goals
- Monitoring system configuration
- Sensor selection
- Sensor performance versus requirement
- Fatigue critical location
- Location of sensors
- Communication strategy
- Installation and retrieval requirement
- Robustness and Integrity requirements
- Cost versus benefits

Current monitoring strategies, configuration are more closely disused in the following section.

Motion Monitoring System

Motion monitoring systems are most commonly used in assesing structrual integrty of key critcal components of the riser, wellhead and conductor system. A typical motion monitoring configuration system is shown in Figure 6. Motion sensors using combination of 3 Axis accelration and 2 Axis Angular rate sensors are distributed along the riser system and distributed such that the response of the riser and wellhead conductor can be indepenedelty measured and verified.

The sensors are deployed either directly during riser run or conveniently using ROV (Remotely Operating Vehicles). Figure 7 show motion sensors deployed on the BOP/LMRP stack and Figure 8 show a motion sensor deployed on the low pressure housing both using ROV friendly magnetic holders.

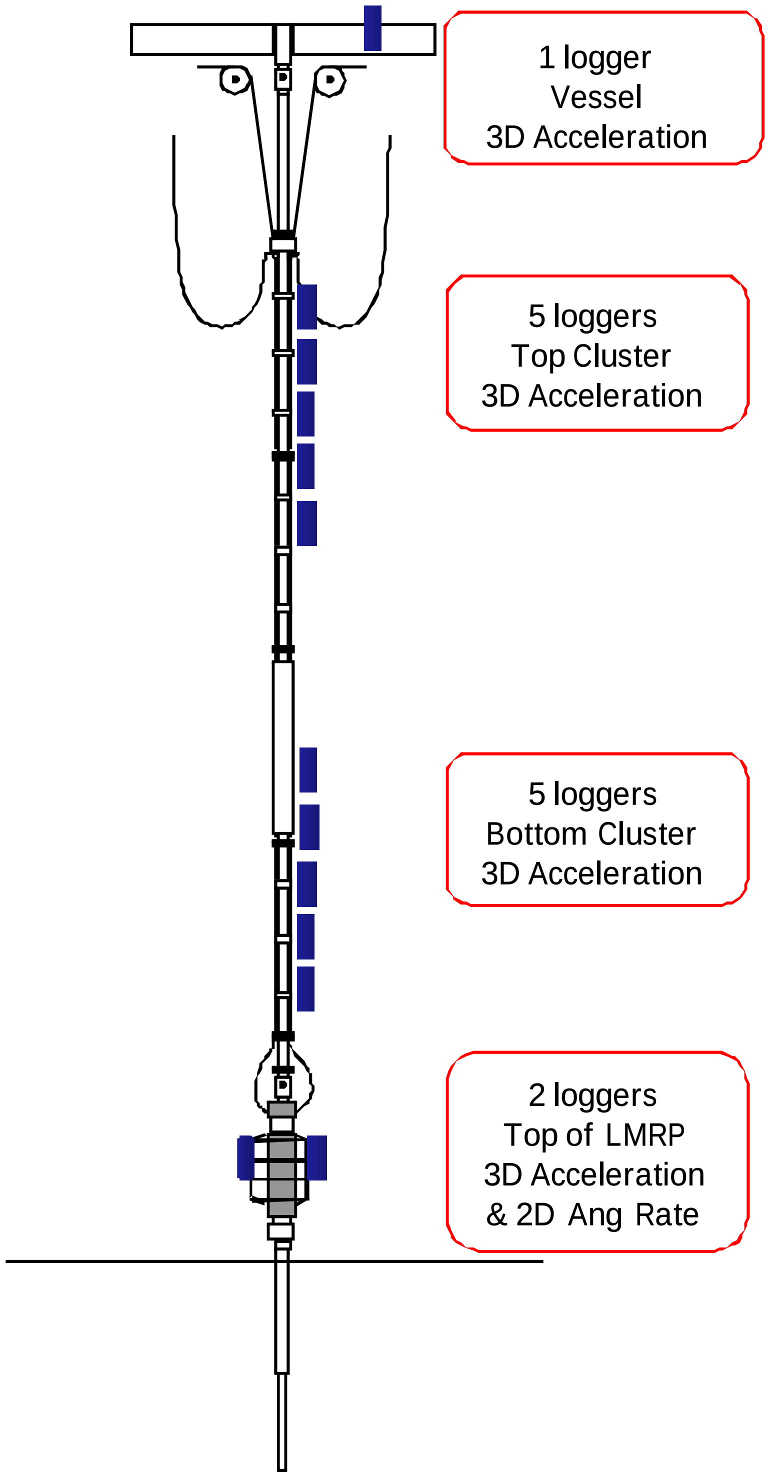

Figure 6 - *Typical Motion Monitoring System*

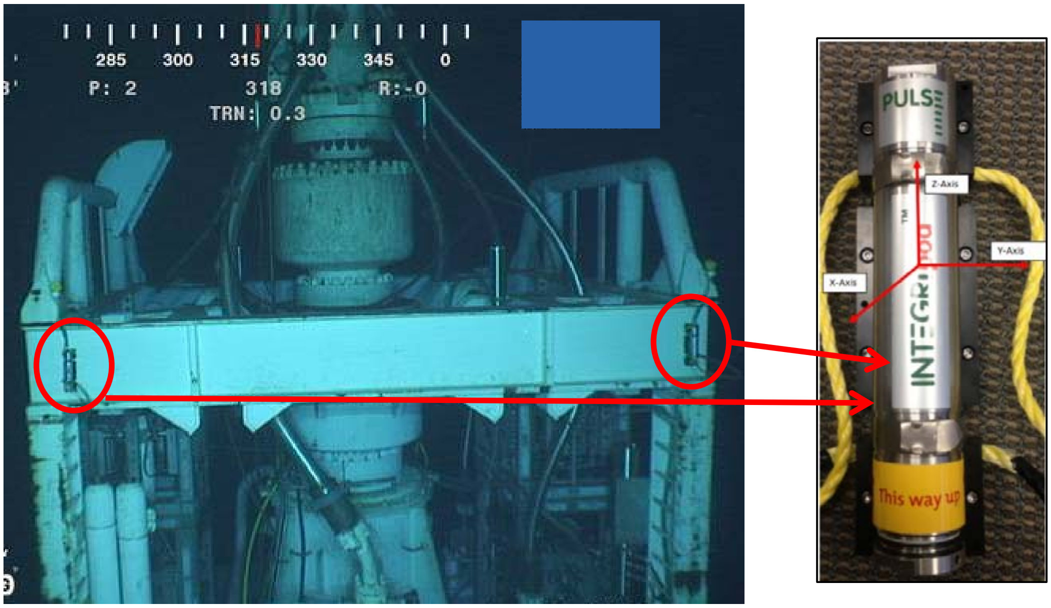

Figure 7 - *Motion Monitoring Loggers Deployed on BOP/ LMRP*

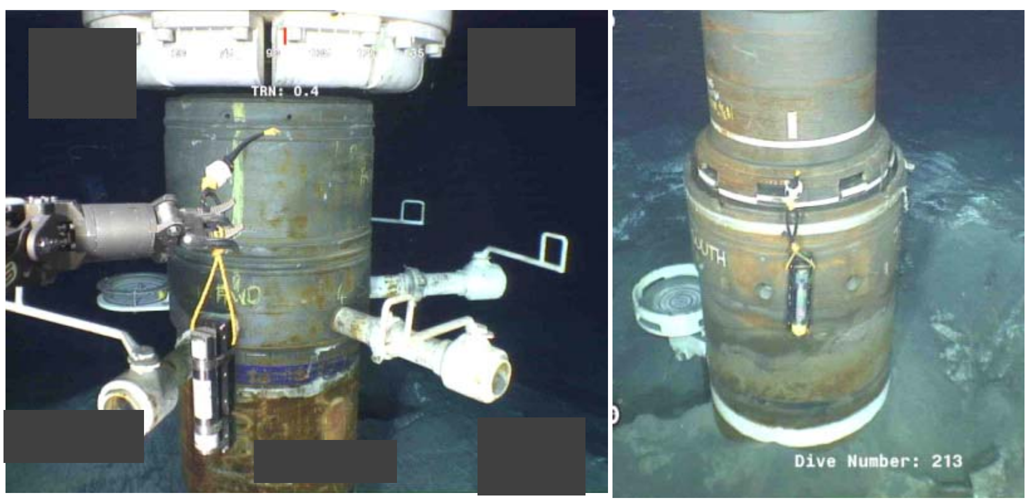

Figure 8 - *Motion Monitoring Loggers Deployed on Low Pressure Housing*

Strain Monitoring Sensors

The output of a strain sensor is a direct strain measurement of the target that they are attached to. The advantage of the localized strain measurement system is that it eliminates the assumptions required for modal response prediction from the motion sensor data, such as damping coefficients. The direct strain sensor measurement therefore requires little data post processing and provide accurate strain range and amplitude frequency information. Simple rain flow calculation can be used to determine accurate fatigue damage rates and total fatigue damage of any riser system component. This directly monitoring the strain at fatigue critical location which may be located, on the upper transition joint above the LMRP and Low Pressure Housing may be seen advantageous in conjunction with motion monitoring systems.

Basic strain measurement systems consisting of bonded strain gauges have been used for drilling riser monitoring system successfully, however the nature of application requirement for bonded strain gauges are difficult to achieve in a production drilling environment therefore may not always be suitable. Alternatively it may be useful to consider of the shelf subsea strain sensor systems, the strain sensors may be mounted over critical area locations in order to capture the strain response of fatigue critical areas. A typical strain sensor application used on production drilling riser is shown in Figure 9. To capture the smallest dynamic curvature changes the strain stick measurement resolution is +/-2 Micro strain. This high sensitivity allows capture of the smallest anticipated bending moment the riser will experience.

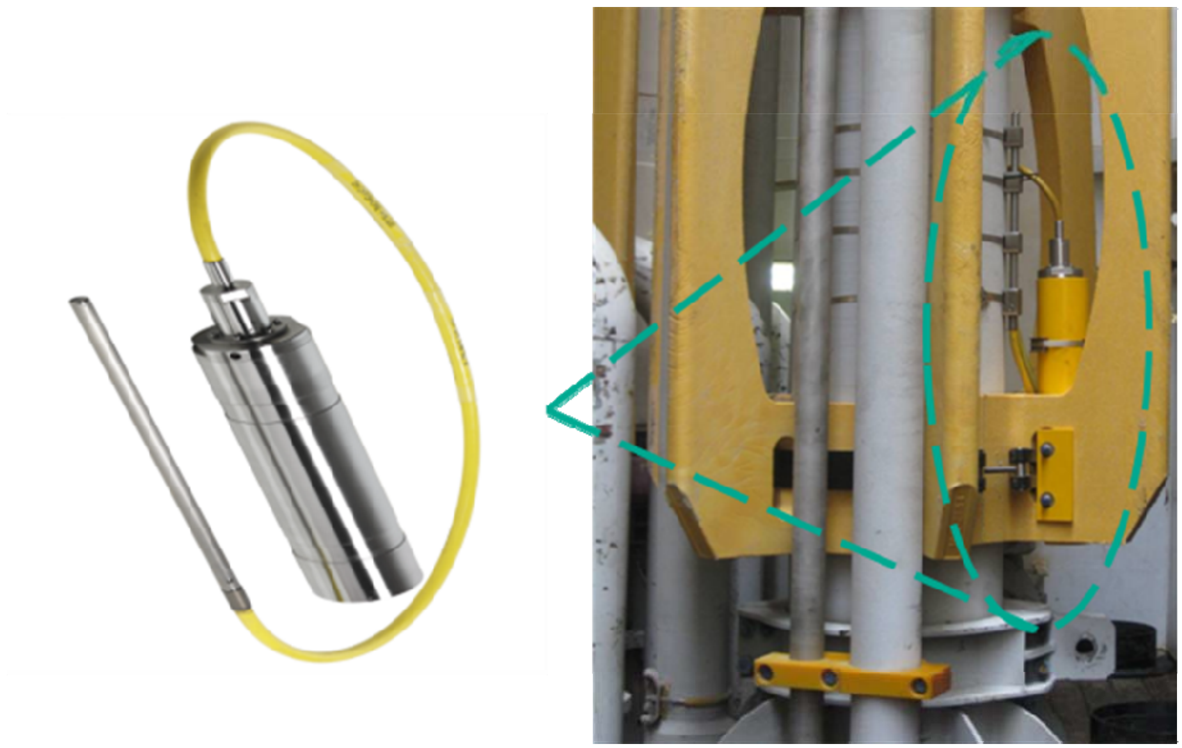

Figure 9 - *Dynamic Strain Monitoring on Drilling Riser*

Communication Methods

In order to conduct safe and controlled drilling operations many operators, as part of their Integrity Management (IM) program, require instant or on demand availability of monitoring data of the drilling riser and conductor system. As determined by the overall monitoring strategy and requirements for data availability it is recommended to clearly define and specify the preferred communication method. Table 2 shows available communication strategies along with consideration factors.

Communication Protocol	Qualification Level [API]	Robustness	Data Availability	Installation Requirement	CAPEX
Standalone	Qualified [TRL7]	high	After Retrival	low	low
Hardwired	Low [TRL3]	medium	Continuous	high	high
Acoustic / Optical	Low [TRL3]	medium	On Demand	medium	high

Table 2 *Comparison of Communication Strategies*

Basic standalone system requires sensors that are powered with on board battery and memory devices. They are very robust and have been in use for many years with great success. Drawback is that the sensors have to be retrieved via ROV or recovery of the drilling riser to obtain the data. However this system is most cost effective and is recommended for drilling application that may require long term fatigue tracking in benign areas only.

Successful hardwired monitoring systems have been deployed on drilling riser successfully. Two (2) option hardwire solutions are available, first one is using and independent cable that is installed and simply clamped to the riser or joke and kill lines during the riser run. Second option is the use of existing MUX cable systems that are used to provide power and communication to BOP pressure, temperature and other vital drilling parameters. Both options require careful planning during the specification stage and strong focus on installation constrains and consideration regarding benefits versus risks has to be taken.

Acoustic and or Optical communication system have been in use in the offshore drilling industry such as Dynamic position systems (DPS) for many years. Currently strong efforts are being undertaken to incorporate integrity monitoring systems into this existing infrastructure. Figure 10 shows an example of a conceptual infrastructure including component design. The benefits of this system are that it does not require installation of a hardwired cable and provides data availability on demand. To aid the limitations in terms of data upload bandwidth requirements each Motion Data Logger (MDL) processes the gathered data in it onboard Central Processing Unit (CPU) to provide either power spectral density or basic statistical information. The data is then transferred to the central CPU that communicated with the acoustic and or optical transponder to upload the information topside. Full data sets are also stored in each MDL and upon recovery or via optical link with the ROV recovered or downloaded in full. Careful consideration have to be taken to the system design, architecture and overall integration into existing communication system to satisfy required monitoring strategies and defined KPI's.

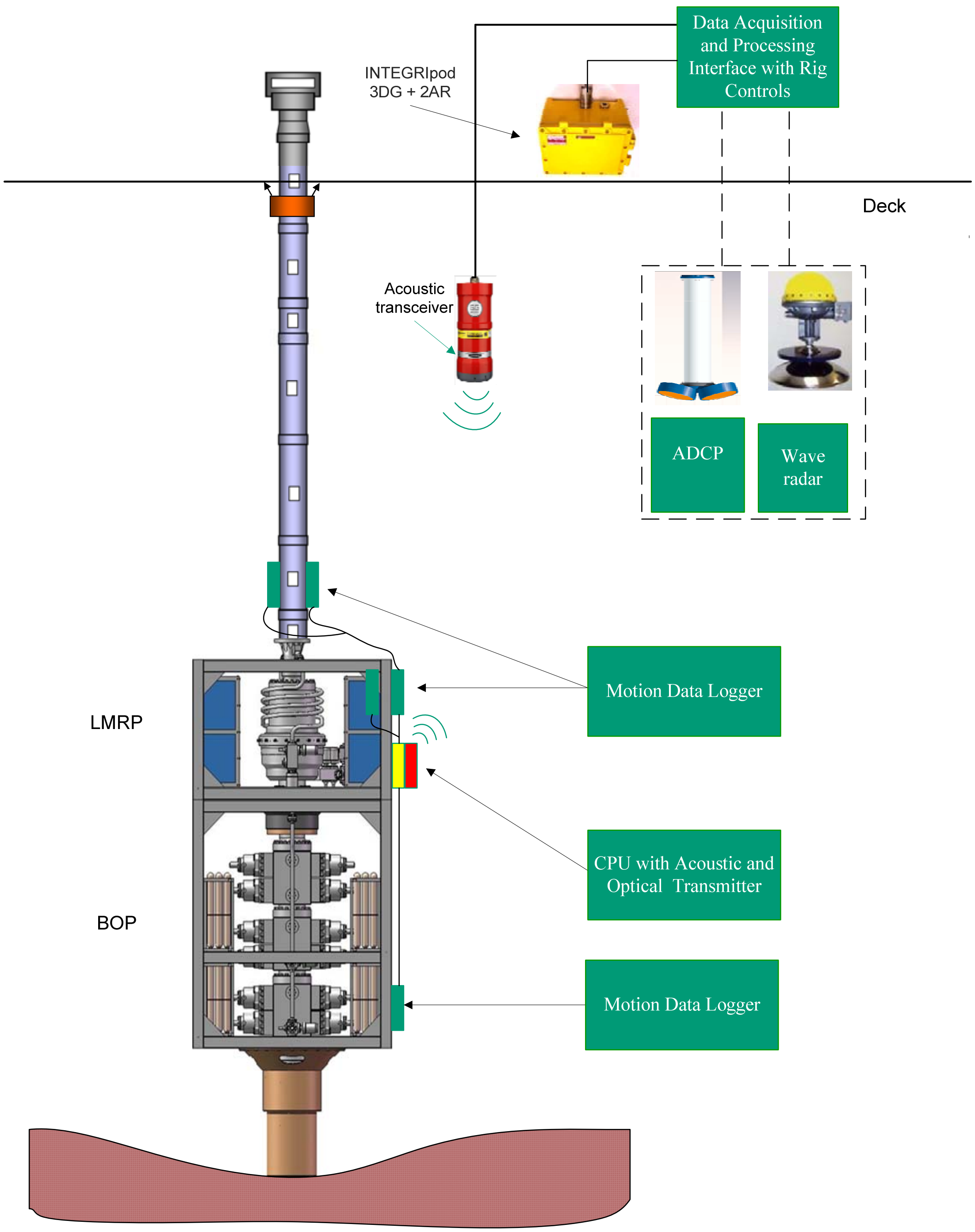

Figure 10 - *Example - Acoustic and Optical Integrity Monitoring System*

Data Processing and Software Interfaces

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 as shown in Figure 11 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.

Post processing of the measured data in both the time and frequency domain allows for the source of the motions to be identified as wave-induced or VIV. The amplitude of the measured motions is then processed into stress range and combined with number of cycles measured to obtain fatigue accumulation. The measured motion response also allows for the analysis models calibration.

Figure 11 - *Example* - *Software with Drilling Specific KPIs*

CONCLUSION

Wave and current induced motions are transferred to the wellhead and conductor system when connected to a drilling riser and can cause fatigue issues. The fatigue damage accumulation is further exacerbated with the increasing BOP stack size, non-optimal wellhead system design, soft soils and longer well operations. As a result, finite element analysis may show marginal wellhead fatigue performance especially in shallow waters, harsh environments and with 6^{th} generation rigs.

Structural monitoring can provide critical data for integrity management of the wellhead systems. It involves component level motion and strain measurements which allows for the actual fatigue accumulation to be determined. Riser, BOP stack and wellhead motion can be measured using accelerometers and inclinometers. Strain monitoring devices can also be used to measure bending loads.

Careful planning of sensor type, sensor location, installation, data management and analysis is required to conduct a successful structural monitoring. A structural monitoring system can be designed for on demand feedback using acoustic or hardwired communication. It can also be configured as standalone system with onboard memory for long term fatigue assessment. The optimum communication method is selected based on the project requirements.

Fatigue tracking tools are enabling technologies that can help in situations where the fatigue life predictions are marginal. Field measurements also provide critical data that can be used to calibrate the models for future analysis.

NOMENCLATURE

ADCP Acoustic Doppler Current Profiler

BOP Blow Out Preventer

DNV Det Norske Veritas

DPS Dynamic Position System

IM Integrity Management Program

KPI Key Performance Indicator

LFJ Lower Flex Joint

LMRP Lower Marine Riser Package

LP Low Pressure

MDL Motion Data Logger

MODU Mobile Offshore Drilling Unit

ROV Remotely Operated Vehicle

TRL Technology Readiness Level

VIV Vortex Induced Vibration

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