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Abstract

Number of intervention operations in subsea wells has been increasing last years. During the intervention operations workover and completion risers are subjected to large environmental loads. Intervention operations are mainly guided by the operational analysis report, though the reports are generated by a computation which is based on conservative standards. Therefore interventions were carried in smaller operational windows than actual.

Failure of subsea intervention equipment can be highly critical and wait on weather time can escalate operation cost substantially. It is due to uncertainties and misjudgments lied under operational analysis. Monitoring techniques can be used for measuring actual state of the workover risers. Data from this monitoring helps for better understanding operational situation and to make better decisions. By doing real-time monitoring companies can operate in larger operational window and make better planning for maintenance.

There are not many companies who is practicing riser monitoring and there is not direct guidance for implementation of riser monitoring system in international standards. In this thesis traditional operation guidance and industrial riser monitoring experiences were presented. Methodology for implementation of riser management system with emphasis on implementation of riser monitoring was created. Process of riser monitoring implementation is described in several steps starting from defining equipment selection and finishing how information presented to the operator. Application of the methodology is illustrated in case study, where riser monitoring system implemented for open sea workover riser.

Acknowledgement

First of all I would like to thank God, who is a reason for everything what I have right now, who gave me loved parents, lovely wife and supportive brother, who gave me trustful friends and for many more things.

I have written the thesis on my work place. I want thank Per Thomas Moe, leader of WAMS team for his individual support and for his trust to give me this thesis.

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Rauan Zhamangarin

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Abbreviations

ADCP	Acoustic Doppler Current Profiler
AES	Acoustic Emission Sensor
API	American Petroleum Institute
BOP	Blow Out Preventers
CBM	Condition Based Maintenance
CT	Coil Tubing
CWOR	Completion and Workover Risers
DNV	Det Norske Veritas
DP	Dynamic Positioning
ECM	Enterprise Content Management
EDP	Emergency Disconnect Package
FBG	Fiber Brag Grating
FEA	Finite Element Analysis
FMECA	Failure Modes, Effects Criticality Analysis
FMSA	Failure Mode and Symptoms Analysis
FPU	Floating Production Unit
FSC	Fail-Safe Closed
GRA	Global Riser Analysis
HSLV	High Set Lubrication Valve
ISO	International Organization for Standardization
JAMSTEC	Japan Agency for Marine - Earth Science and Technology
KOGT	Kongsberg Oil and Gas Technologies
LMRP	Lower Marine Riser Package
LRP	Lower Riser Package
MPN	Monitoring Priority Number
NCS	North Continental Shelf
NPD	Norwegian Petroleum Directorate
PSM	Preservation Storage and Maintenance
RAMS	Riser Anchor Monitoring System
RAO	Response Amplitude Operator
RBI	Risk Based Inspection
RBM	Risk Based Maintenance
RFMS	Riser Fatigue Management System
RLWI	Riserless Light Well Intervention
RMS	Riser Management System
ROV	Remote Operating Vehicle
SCF	Stress Concentration Factor
SFT	Surface Flow Tree
SVDL	Subsea Vibration Data Logger
TTRD	Through Tubing Rotary Drilling

USJ	Upper Stress Joint
VIV	Vortex Induced Vibration
WAMS	Well Access Management System
WAS	Well Access Systems
WCP	Well Control Package
WL	Wireline
WO	Workover
WOCM	Worover Control Module

1. Introduction

There is a high focus on safety for the offshore operation both in terms of safety of personnel and environment. Accident happened with Deepwater Horizon emphasized the crucial role of the safety in offshore industry. Number of workover operations performed in Norwegian Continental Shelf (NCS) has increased in recent years, and there is high concern regarding integrity of subsea equipment used in operation. Codes from American Petroleum Institute (API), Det Norske Veritas (DNV) and International Organization for Standardization (ISO) are suggested to follow by Norwegian Authorities in NCS. Standards do not state any direct guideline for fatigue tracking and monitoring of Well Access System (WAS) equipment.

1.1. Motivation

Depletion of old oil fields in Norway was the main reason for decrease of petroleum production in recent years. According to Norwegian Petroleum Directorate (NPD) cost effective intervention activities can trigger to increase the oil recovery factor in mature fields. The report "Økt utvinning på norsk kontinentalsokkel – En rapport fra utvinningsutvalget." indicated that an increase of oil recovery only for 1% can give profit around 340 bn NOK (Energy, 2010).

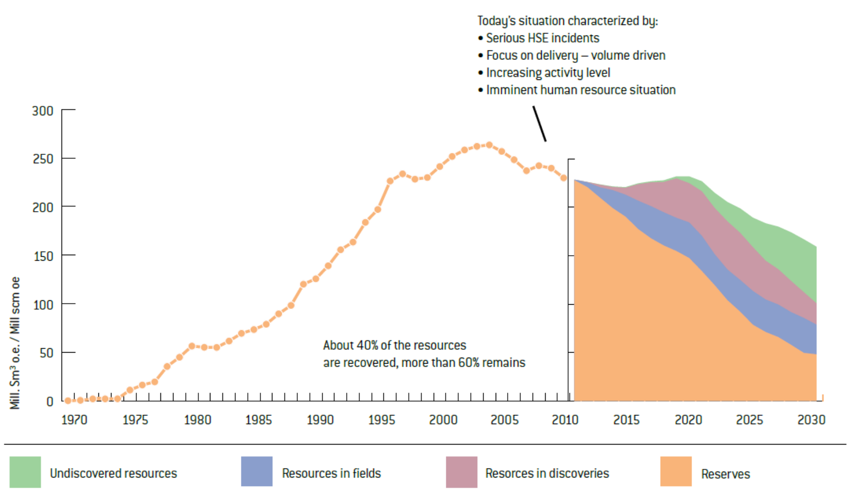


Figure 1 Petroleum production history and forecast (NPD, 2013)

Most of the intervention activities carried out in open sea by following the operational guidelines which is barely based on preoperational analysis. Guided by different standards and codes the preoperational analysis usually comes up with over conservative operational window or operational time. This limitation on the operational guidelines directly can escalate the cost of the operations due to more frequent inspections on the workover risers, longer operational time due to conservative weather windows.

Ability to measure the actual state and condition of the equipment used during operation can cause in larger operational window, better maintenance and inspection planning. Therefore, implementation of riser monitoring system can lead to cost saving and ensure integrity of the operations.

WAS is the department in FMC which deals with equipment and operation to bring access to subsea well. WAS provides Completion and Workover Risers (CWOR), Through Tubing Rotary Drilling (TTRD) and Riserless Light Well Interventions (RLWI) solutions for the operating companies. FMC as a supplier of the well access systems highly interested in implementation and providing riser monitoring system for their costumers

This paper gives guideline for riser management and implementation of the riser monitoring system for WAS.

1.2. Goal and scope

The scope of this thesis is to show the whole cycle of riser management system, existing maintenance and inspection regimes for workover risers; give brief information about the riser monitoring systems used in the market and recommend riser monitoring system establishment strategy.

The main goals of this thesis are:

- Show existing operation and maintenance planning strategies
- Investigate different riser measurement techniques used in the industry
- Recommend riser management system which adds value for workover operations

- Recommend methodology for establishment of riser monitoring system, which gives real-time information about the state of the equipment, can advise for operation and for maintenance or inspection.
- Show the application of the methodology with use of case study.

1.3. Methodology

In the beginning literature review was done about workover riser system. Special emphasis was placed on failure modes, especially fatigue issues. Then investigation was done about fatigue monitoring techniques used in other industries and the FMC's competing companies.

DNV standards regarding Riser Integrity Management, Riser Fatigue and Fatigue of steel structures were reviewed, ISO standards regarding CWOR system and condition monitoring guidelines were examined. The guidelines found to be general and general guideline for implementation methodology for riser monitoring system for FMC was created as a flowchart. To illustrate use of the methodology case study was performed.

Thesis was written in FMC's office in Kongsberg in a department of WAS. During the semester author had a chance to work with new riser monitoring system in FMC which is under research and development, take part in software development process for the system, had a chance to talk with product owner and person who is in charge for well intervention services in order to get better overview over the system. Moreover, author has reviewed condition monitoring techniques used in FMC for Subsea Production System, get better understanding about subsea system and physics used behind the riser monitoring.

1.4. Delimitation

Due to time limitation and resource constrains the paper was limited with general research about riser monitoring system. The author will just give brief introduction about monitoring sensors, data acquisition technologies, inspection tools, because all of those subjects can be reviewed individually and might require more time and competence for analysis. Some numbers used for cost analysis are rough estimations of the actual cost based on colleague's opinion. Although riser itself quite simple equipment it has many ways to fail and the thesis was mainly concentrated for fatigue failure and excessive yielding failure issues, the other failure issues like wear, tear or corrosion can be considered as a different subject and require other research for explaining.

2. Theory

This chapter is intended to give a broad overview about workover risers. The chapter is divided into several subchapters as:

- Well Access System
- Riser design
- Maintenance and inspection
- Riser monitoring system.

The first sub-chapter gives information about type of the operations used for intervention, type of the risers used for operation and functions of the each component on the riser.

The second sub-chapter gives information about design of the riser system in general and each riser components. The subchapter also gives information how results from global structural analysis can be used for operation planning and maintenance planning.

The third sub-chapter gives overview regarding how inspection is planned currently in the industry, gives overview about the techniques used for the planning and codes used as guidance.

The final sub-chapter describes use of riser monitoring system, benefits of implementation and characteristics. At the end riser monitoring system used by different companies are presented.

2.1. Well Access Systems

Well access system is one of the deliverables what makes up Subsea Production System. Access in the context means to access the subsea well, i.e. preparation, completion and maintenance of the well, in order to increase the production or ensure the well integrity. The operations are:

- Installation and retrieval of Xmas trees
- Installation and retrieval of Tubing Hangers
- Installation and retrieval of Tree Caps (for Horizontal Xmas tree)
- Well intervention activities with wireline and coil tubing
- Production test through workover system
- Hydraulic fracturing in reservoirs with low permeability

- Through Tubing Rotary Drilling (side track drilling) to increase production rate in existing well.

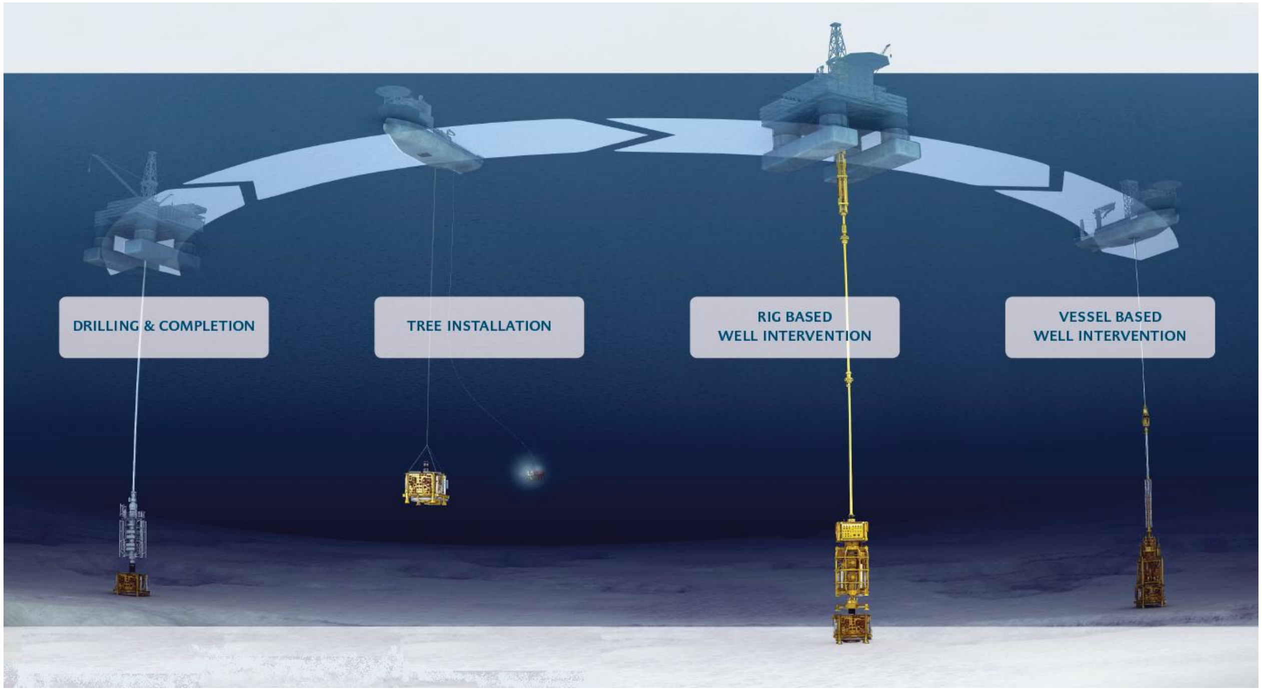


Figure 2 Overview of WAS (FMCTI, 2013)

Increased depth for subsea well makes more difficult to access the subsea wells. High renting cost of rig triggers to use simpler, smaller tools. Well interventions categorized into three types depending on type of the vessel and equipment. All three types of intervention are described below:

- Category A – Riserless light well intervention (RLWI)

  As the name states, the intervention operations are deployed without riser system, the later may result in choosing smaller monohole vessels ensuring huge cost saving for the operators. Riserless Light Well Interventions are mainly aimed for less complex intervention operations, therefore sometimes it is referred as light workover (FMC, 2013). RLWI operations include:

  - Perforation and logging
  - Installation and retrieval of small well equipment like plugs.

- Category B - Open sea mode , workover operations

In this category workover risers are used in order to conduct intervention operations, which enable to perform more complex operations. Workover riser establishes direct link between rig and subsea well. The well intervention services conducted without retrieving existing Xmas trees and smaller semi-submersible vessels are utilized. Therefore it reduces heavy lift operations and less power requires for the system compared to conventional vessels. It is feasible to perform the following operations in Category B (FMC, 2013):

- Drilling (TTRD)
- Wireline
- Installation and retrieval of plugs
- Installation and retrieval of Xmas trees
- Test production
- Coil tubing.

- Category C- In-riser mode, workover operations

Category C operations are performed by marine or drilling risers. The system designed to perform more complex operations. The well control package (WCP) from Category B interventions replaced by blow out preventers (BOP) to control the well. Usually BOP and Marine risers used by conventional drilling rig which makes it most expensive intervention operations. The in-riser mode operations are (FMC, 2013):

- Drilling
- Installation and retrieval of Xmas tree.
- Test production
- Wireline
- Coil tubing Operations
- Installation and retrieval of plugs.

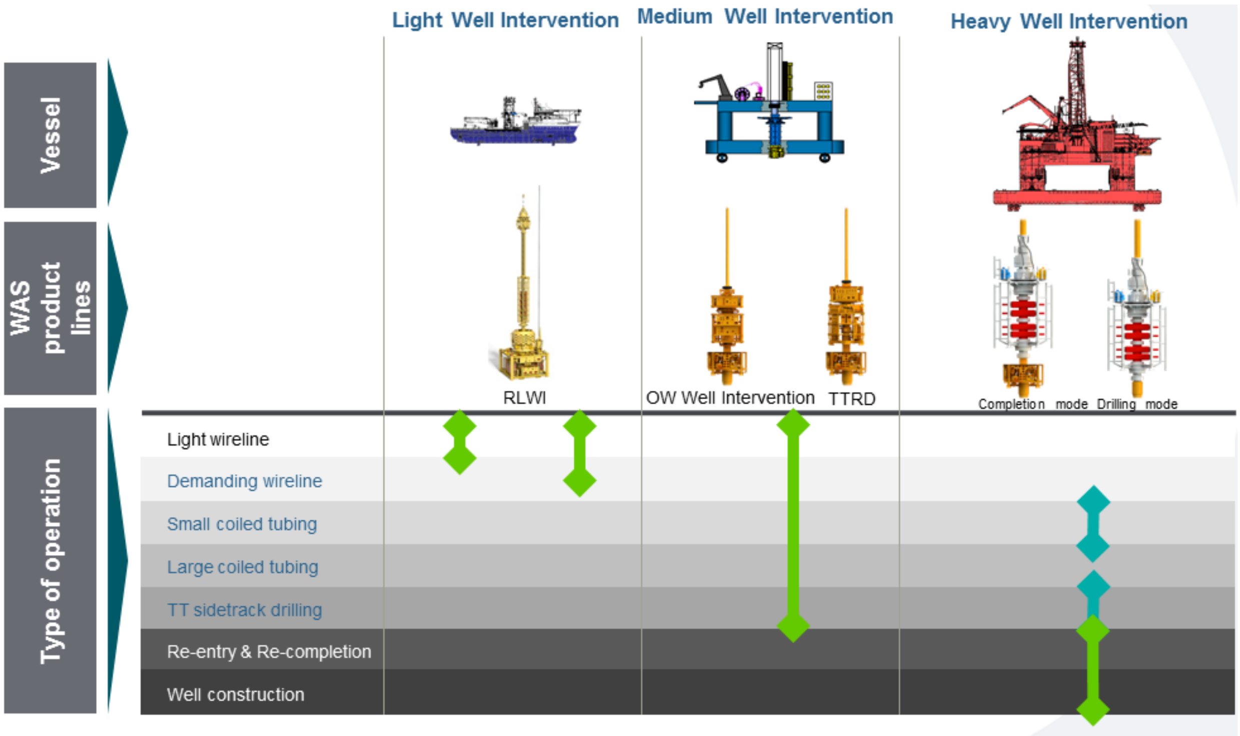


Figure 3 Category A, B, C intervention operations (Mazerov, 2011)

2.1.1. Open Sea Workover Risers

Figure 4 shows the riser joints what makes up workover risers. Each joint has specific functional requirements. This chapter is limited only by brief definition of each riser joint used for workover operations.

- Lower Riser Package (LRP): LRP is a package which enables to control the well in all situations. It is situated between Emergency Disconnect package (EDP) and x-mas Tree. Spring actuators and local accumulator enable LRP to close all barriers automatically if failure occurs, which makes it failure-safe closed (FSC) tool. LRP can even cut wireline or coil tubing and stay still connected in case of emergency quick disconnect.

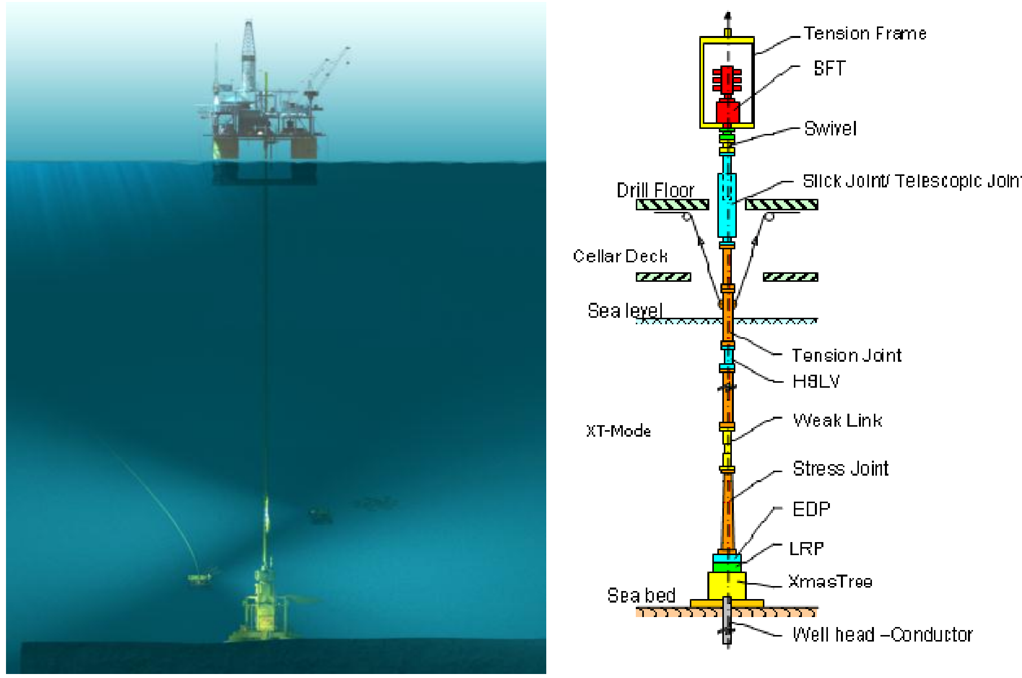


Figure 4 Illustration of workover riser (FMC, 2013)

- Emergency Disconnect Package (EDP): EDP is a package which implements planned or emergency disconnection. EDP is connected to Workover Control Module (WOCM), which operates workover stack hydraulics.
- Weak link: weak link is the weakest link in the riser stack designed to rupture if the riser string subjected to an excessive tension, i.e. weak link created in a way to rupture first before well barrier elements and wellhead. The analysis required determining point of rupture of weak link for each system, and it can be obtained based on operational factors.
- High Set Lubricator Valve (HSLV): the HSLV is the integral part of the riser system and located in the upper section of the riser joints. The HSLV is hydraulically managed valve used to isolate well pressure when it is required.
- Riser joint: FMC uses standard 45 feet union nut riser joint. The joint can be mono bore (production only) or dual bore (annulus and production). These joints mainly used in mid part of the riser stack.
- Tension Joint: tension joint is a joint located below upper stress joint (USJ) and connected to the rig via rucker wires and a tension ring. The main purpose of the tension joint is to

keep constant tension on the riser to avoid problems with fatigue. Total weight of the riser joint is important for the tension joint design.

- Telescopic Joint: main function of the telescopic joint is to compensate for the relative movement of riser and rig surface. Using the telescopic joint speeds up rigging operations for Surface flow Tree (SFT), wireline (WL), Coil Tubing (CT) etc.
- Swivel: main purpose of the swivel to allow rotate riser joints without rotating SFT. Dynamic Positioned (DP) vessels can change their directions without twisting riser stack.
- Stress Joint: enables safe transfer of the load between WO riser and EDP. There are mainly two types of stress joints: upper stress joint and lower stress joint. Stress Joints are supposed to take high loads during operations, i.e. smoothly reduced diameter in mid part of the stress joint reduces bending loads on both interfaces such as stress joint to riser interface and stress joint to subsea equipment interface (Abadi, 2003).

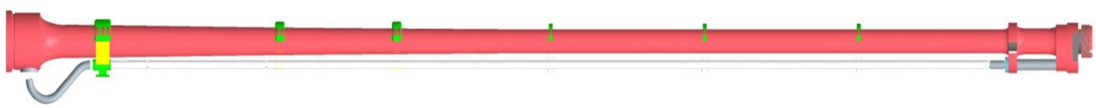


Figure 5 Lower stress joint

Most of the information about WO riser components was taken from FMC Subsea school documents (FMC, 2013).

2.2. Riser Design

The Figure 6 illustrates the failures of the riser components. Integrity of the riser components directly depends on how it is designed for the operation and for the maintenance.

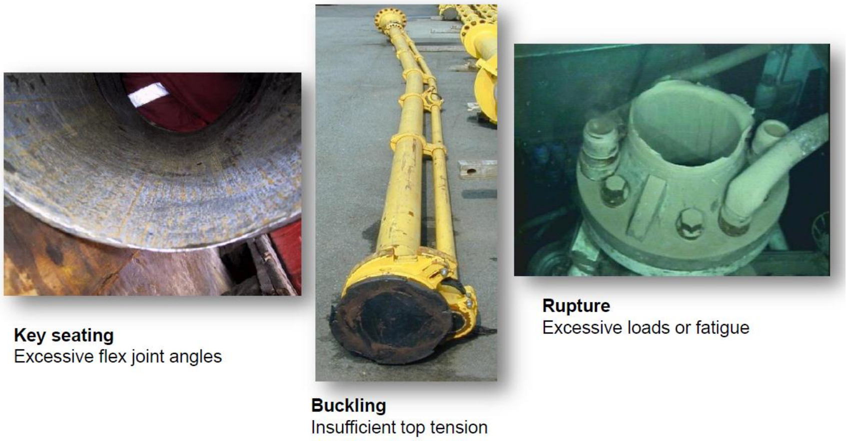


Figure 6 Failure modes (Jensen G. , 2013)

Regarding ISO standard during the design of the riser system as minimum the following failure modes need to be considered (ISO-13628-7, 2006):

- Excessive yielding
- Buckling
- Fatigue
- Brittle fracture
- Excessive deflection
- Leak- tightness
- Corrosion and wear
- Mechanical function.

WAS is complex system containing different equipment for the operations. So design of the system and design of the sub-system equipment need to concur together. In order to verify that design is correct and safe enough to operate, the system is simulated by using structural analysis tools. The simulation of the system required to mimic the real situation on the sea.

For the riser system mainly two types of the structural analysis are defined: global riser analysis (GRA) and component analysis (Williams, 2010). In this chapter description of the both analysis and applications of them is discussed.

2.2.1. Global Riser Analysis

Global riser analysis basically answers for two main questions:

- How the riser systems need to be operated?
- How long riser needs to be operated?

An operational window, sometimes also referred as operational limitation is safe operating zone for the vessel in given wave height. Typical illustration of the operational window can be seen in the Figure 7, whereas the window given as a circle line around the vessel.

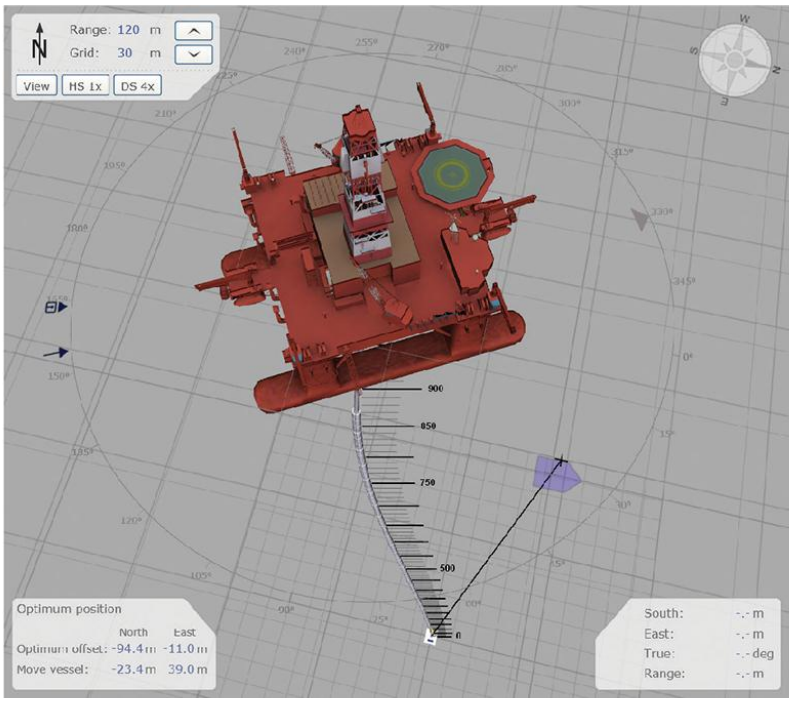


Figure 7 3-D illustration of the vessel and operational window (Jensen G. A., 2013)

The GRA mainly intended to predict the riser behavior under operating conditions, determine optimal top tensions, determine fatigue exposure of components and as it is mentioned before operational window.

It is not possible to model each single riser component in global analysis, because it needs enormous computational resources. In order to make the calculation simple the riser stack is modeled as simple beam elements, but with same mechanical properties as riser joints. The

Figure 8 shows the general structure of GRA process. Main required input parameters are in blue boxes whereas the result from the GRA shown in green boxes.

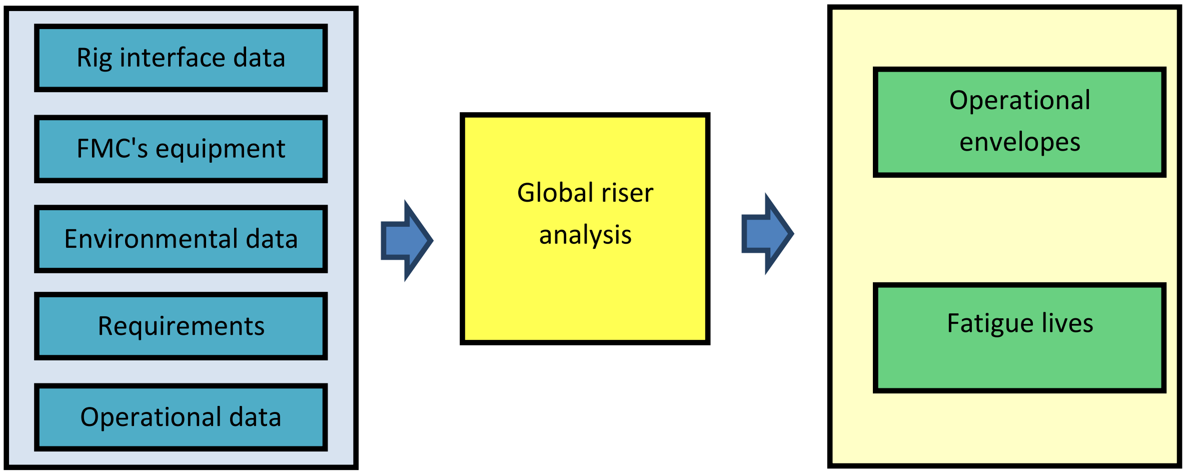


Figure 8 Global riser analysis Structure

The required inputs for the analysis can be described in more detail as below:

- Rig interface data : all information regarding vessel motion and interface should be included in the analysis, for example :
  - Vessel characteristics: dimensions, draft, type etc.
  - Motion characteristics: vessels motion in terms of wave motion, (RAO's or second order motion)
  - Station-keeping characteristics: mooring line configuration, dynamic positioning, positioning tolerance etc.
  - Hull Geometry: pontoon spacing, moonpool geometry,
  - Draw work motion compensation: active or passive compensator characteristics.
  - Information regarding derrick and drill floor: maximum lift height, rotational support.
  - Tensioner characteristics: capacity, number, dimensions etc.
  - Vessel's orientation.
  - Vessel's offset.
- Equipment information: information regarding mechanical behavior of riser joint is obtained by component analysis (Chapter 2.2.2). Component analysis conducted for each joint to obtain following information:

- Capacities: bending and tension capacity
- Fatigue data: SCF's, hot-spot locations
- Stiffness: bending and tension stiffness
- Information about connectors: capacities.

- Environmental Data:
  - Water depth information: minimum/maximal/mean tidal variation
  - Seawater data: density, pH value, temperature etc.
  - Air temperature: minimum/maximum temperature during storage and transportation
  - Soil characteristics: weight, shear strength, type etc.
  - Current information: current profile, direction etc.
  - Wave data: wave spectra, signification wave height and periods etc.
  - Wind data: return period, function of wave on direction, height above sea level etc.
- Requirements:
  - Different standards and codes: API, DNV, ISO etc.
  - Company regulations
  - Governmental regulations etc.
- Operational Data:
  - Type of the operation: Open Sea, In Riser mode etc.
  - Type of the equipment used
  - Type of the intervention: Coil Tubing, Wireline etc.

Afterwards the operational window for the operation and estimated fatigue life will be found (Figure 10 and Figure 11).

While calculating operational window for the operation, the limitations of the each equipment will be considered, so the operational window for each equipment will be build, after that the area or zone encompassing all operational windows will be chosen as suggestible zone to operate. For finding fatigue life of the equipment actual load history and equipment's fatigue parameters are required. One of those parameters is high concentrated stress values on different spot, material and media and so on. The illustration of fatigue life estimation process is shown in the Figure 9 and more detailed information about the process given in the following chapters (FMCTI, 2013).

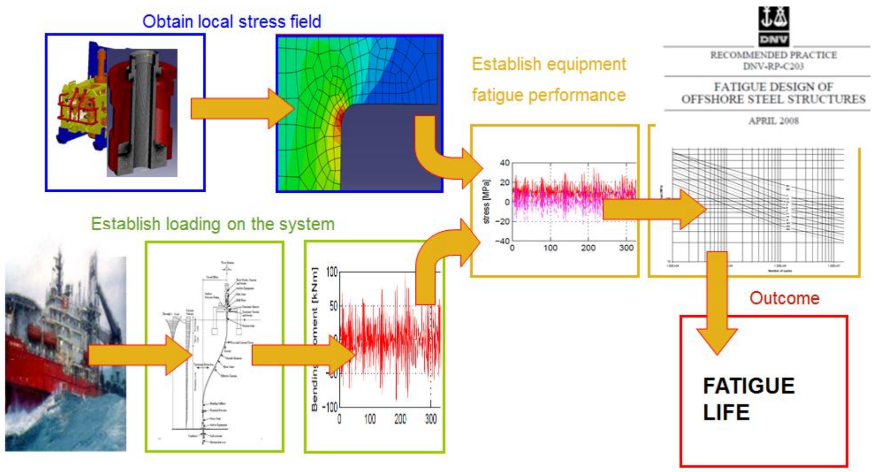


Figure 9 Fatigue life estimation process (FMCTI, 2013)

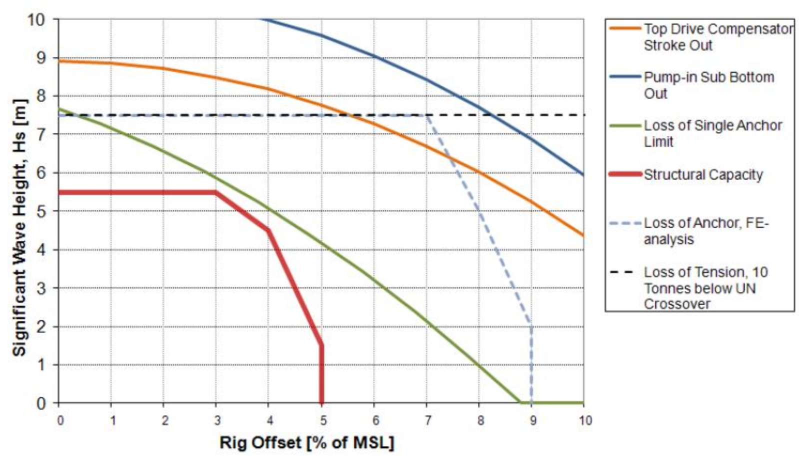
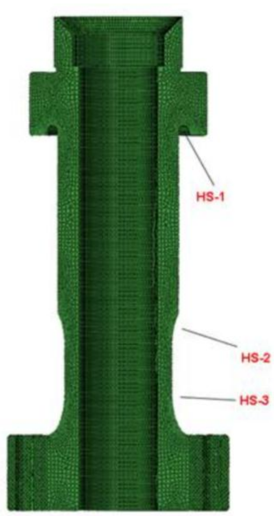


Figure 10 Operational Limitation for XT installation (FMCTI, 2013)



Hot-Spot	SN-Curve	SCF	Life [days]
HS-1	High strength cp	0,528	45
HS-2	High strength cp	1	152
HS-3	High strength cp	1	251

Figure 11 Fatigue live result from GRA

2.2.2. Component analysis

Main reason to conduct component analysis is to get essential information about component (riser joint, connector or wellhead etc.) and use this information in GRA. In the Figure 12 typical illustration of component analysis is given, where we can see bending capacity of the riser joint, bolt capacity and connector's capacity.

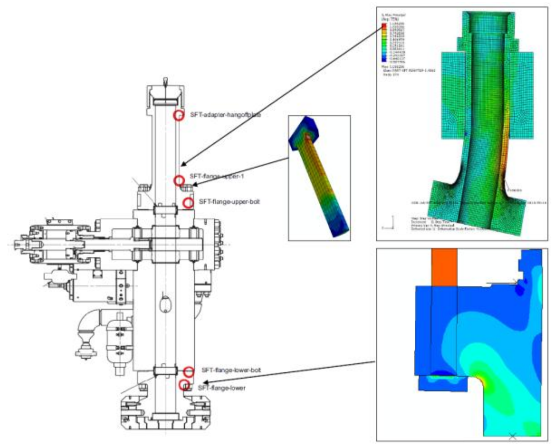


Figure 12 Illustration of component analysis

Component analysis usually conducted by Finite Element Analysis (FEA) tools like ABAQUS or ANSYS. The geometry, material properties and load cases information for the component are required for the analysis to get:

- Gain product knowledge: behavior of the component under different loads, stiffness etc.
- Establish capacities: bending and tension capacities, loss of preload, leakage capacity etc.
- Fatigue related information: Stress Concentration Factors (SCF) and hot spots.
- Design optimization: by knowing required capacities it is possible to optimize the design of the component.
- Verify actions: assure that lifting or pressure testing is safe etc.

Another component that involved in global riser analysis is wellhead. An accident in West Shetland in early 80's has raised awareness about the wellhead integrity, where wellhead fatigue failure happened only in 29 days (Hopper, 1983). The typical illustration wellhead failure due to fatigue is shown in the Figure 13. To get realistic result the wellhead and its boundary conditions should be modeled correctly for component analysis. There are many inputs need to be considered during the modeling. The following list shows typical input for wellhead analysis:

- Wellhead geometry.
- Interactions:
  - Weight of the casing
  - Contact forces between wellhead and pipes
  - Static loads from BOP and riser
- Material properties.
- Friction and contact forces.
- Soil characteristics.

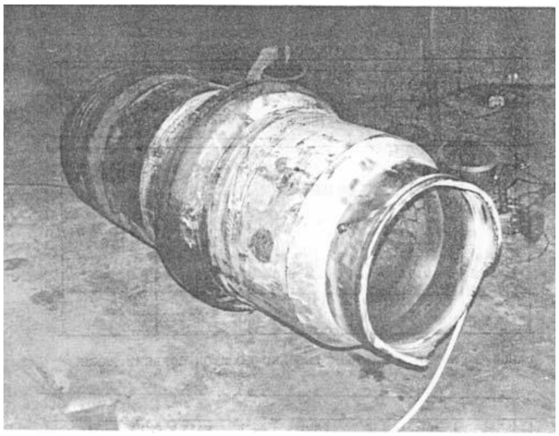


Figure 13 Wellhead failure on welded area (Hopper, 1983).

And the following results obtained from the Wellhead analysis are used in GRA (Holm, Holden, & Russo, 2013).

- Wellhead stiffness
- Stress transfer function.

Finally, as it is discussed in the beginning of this chapter the design optimization of the components can be expressed by the process chart given in the Figure 14. The process chart can be explained by the following way; by running GRA the limiting components can be found in the system, those components can be redesigned by using component analysis. The result from the component analysis for the new design will be implemented for new GRA until the results will be acceptable.

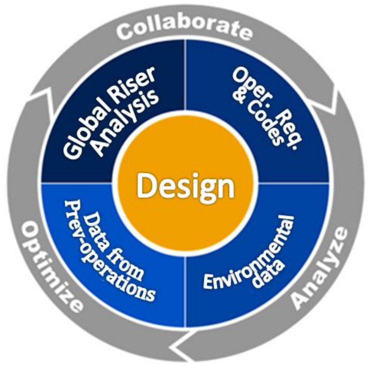


Figure 14 Component design process

2.3. Maintenance and Inspection

Since the operational aspects of the riser were described in chapter 2.2.1, this chapter describes the conventional maintenance and inspection planning for the workover risers.

FMC has mainly six types of maintenance types for its riser system:

- Mobilization
- De-mobilization
- In Storage Maintenance
- Periodic Maintenance
- Mandatory Maintenance
- Incoming Goods Inspection

Most of these activities intended to extend the life of the equipment by cleaning, and inspecting the surfaces and preserving it. The DNV-RP-F206 gives some guideline for preservation, storage and maintenance (PSM) of the equipment.

Risk based inspection (RBI) is carried out for the riser joints in order to be sure that probability of fatigue failure satisfies pre-defined requirements for the operations.

WO operations involve number of uncertainties regarding to fatigue design of mechanical components.

- Fatigue capacity of the riser's material.
- Exposed loads due to wave, current, vessel etc.
- Calculation of the fatigue damage due to loads.

According to probabilistic concept, it is assumed that probability of the fatigue failure is quite small in the beginning of riser's service life but it will gradually increase by the service time of the riser component. When the probability factor of the fatigue failure reaches some level some actions should be taken either by replacing the riser component or conduct inspection to assess remaining fatigue life of the equipment.

According to fracture mechanics initial crack will let to rupture the riser, so the inspection needs to be carried out in order to find any cracks and if it exists, determine size of the existing cracks. By knowing initial crack and its dimension it is possible to build fatigue crack growth model and estimate remaining fatigue life.

Several inspection techniques can be used to inspect initial fatigue crack of the equipment.

- Visual Inspection
- Magnetic Particle Inspection
- Ultrasonic Testing
- X-ray Inspection

The Figure 15 shows the illustration of the RBI planning, whereas required probability of failure due to fatigue is $10^{-3,5}$ and initial probability of the failure is really small less than 10^{-6}. So, each inspection should be planned for the time when probability of the failure will reach $10^{-3,5}$, and if any crack is not found it should be adjusted to initial probability of failure, otherwise based on the crack size the riser joint need to be replaced or repaired by grinding and new probability of failure need to be reassessed.

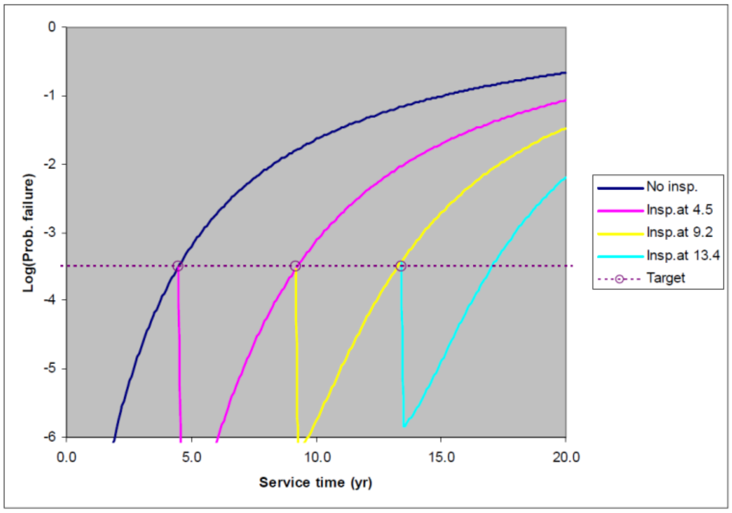


Figure 15 Risk based inspection planning

Inspection planning can be done by two ways either by using stress range to number of cycles model (SN - Model) or by using crack growth model (DNV-OS-F201, 2010). In both cases the analysis performed for special fatigue vulnerable spots on riser components called hot-spots. Figure 16 shows the flowchart for risk based inspection, whereas the processes in the chart will be explained in the following chapters.

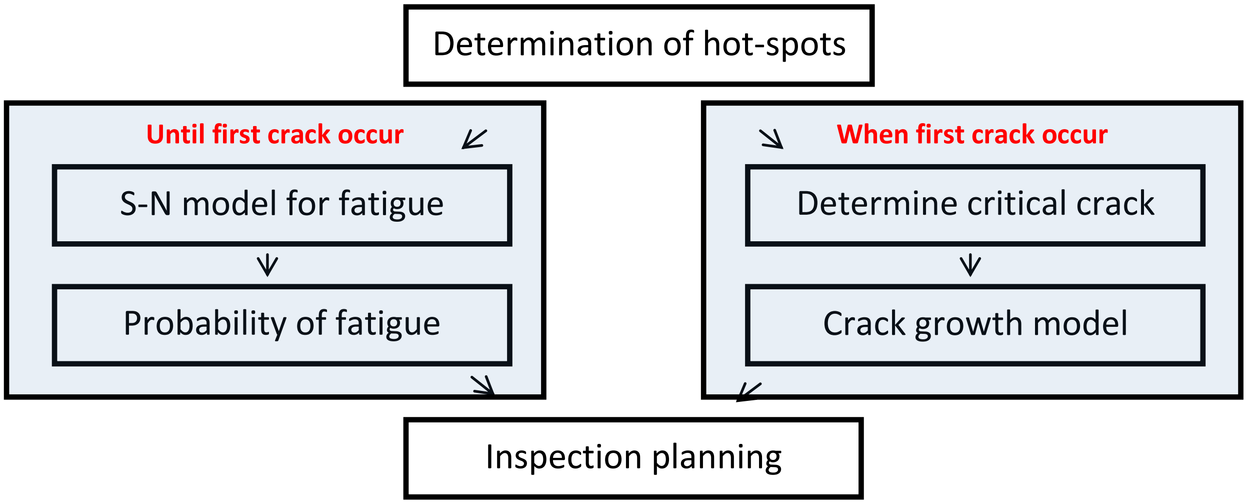


Figure 16 RBI flowchart for inspection planning

2.3.1. Selection of Hot-Spots

The each component susceptible for the fatigue has potential spots where is most likely to initiate. This spots in the industry called hot-spots. Hot-spots usually occur on places where component has geometrical discontinuities. The geometrical discontinuities result on high stress concentrations, the ratio of the stress in hot-spots to stress in remote place called stress concentration factor (SCF). Illustration of the fatigue hot-spot is shown in the Figure 17, where hot-spot shown in red color indicating high stress. So for the each riser component all potential hot-spots with high SCF need to be defined in the beginning. One way of finding of values of SCF is to preform component analysis by using FEA tool.

All the parameters of the hot-spots have to be recorded and will be used for inspection planning and for maintenance. Hot-spots are potential spots for the fatigue inspection as well.

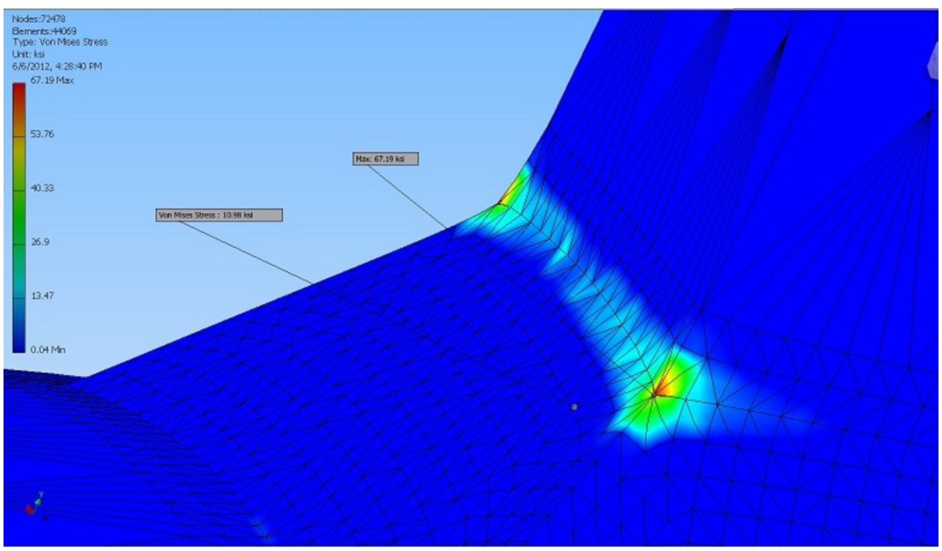


Figure 17 Fatigue hot-spot

2.3.2. Crack growth model

Fracture mechanics can be used to model fatigue crack growth. The model is used to determine acceptable crack size and for scheduling next inspection.

In order to determine the time for planning next inspection, the number of cycles required for initial crack to reach critical crack size. This number can be found by knowing:

- The distribution of nominal range stress needs to be determined in advance in hot-spots.
- Proper crack growth law should be taken for marine environment. For instance according to BS 7910, the Paris Law can be used. The crack growth value should be taken as mean value plus 2 standard deviations.
- Determining initial crack/defect size in riser remained after NDT or fabrication (ISO-13628-7, 2006).

All the other technical details of fatigue crack growth given in Appendix A.

In case of absence of weld joint in riser joint and high level of surface finish, it is expected that the crack initiation will come before than crack-growth model. In order to separate those phases initial crack with 100 mkm is need to be used. The crack-growth model gives rough estimated time of critical crack depth.

2.3.3. S-N Fatigue analysis

S-N curve is a graph showing relationship between altering stress range and number of cycles to failure due to fatigue, typical illustration of S-N curve shown in the Figure 18. General S-N curve analysis for CWOR based on DNV-RP-C203. S-N curve should be appropriate for geometry of component, material of component, stress change direction on component, surrounding environment, method of fabrication and surface finishing.

According to ISO 13628 -7. C .2.2. nominal bending stresses on pipe type riser on both sides can be computed by the following way.

$$\Delta\sigma_{nom.i} = \frac{16 \cdot \Delta M_i \cdot (D_o - Di)}{\pi \cdot (D_o^4 - D_i^4)}$$

Where ΔM is bending moment range.

The local or stress ranges on hot spots can be calculated based on SCF.

$$\Delta\sigma_i = SCF \cdot \Delta\sigma_{nom.i}$$

Then accumulated fatigue damage will be calculated by using Palmgren - Miner's rule:

$$D_{SN} = \sum_{1}^{k} \frac{n_i}{N_i} = \frac{1}{a} \sum_{1}^{k} n_i \cdot \Delta\sigma_i^{\,m} \leq \frac{1}{D_F}$$

Whereas D_F, D_{SN}, a, m are represents design fatigue factor, accumulated fatigue damage, characteristic fatigue strength and negative inverse slope of S-N curve respectively. So by knowing load distribution for specific period of time, it is possible to determine design fatigue life of the component.

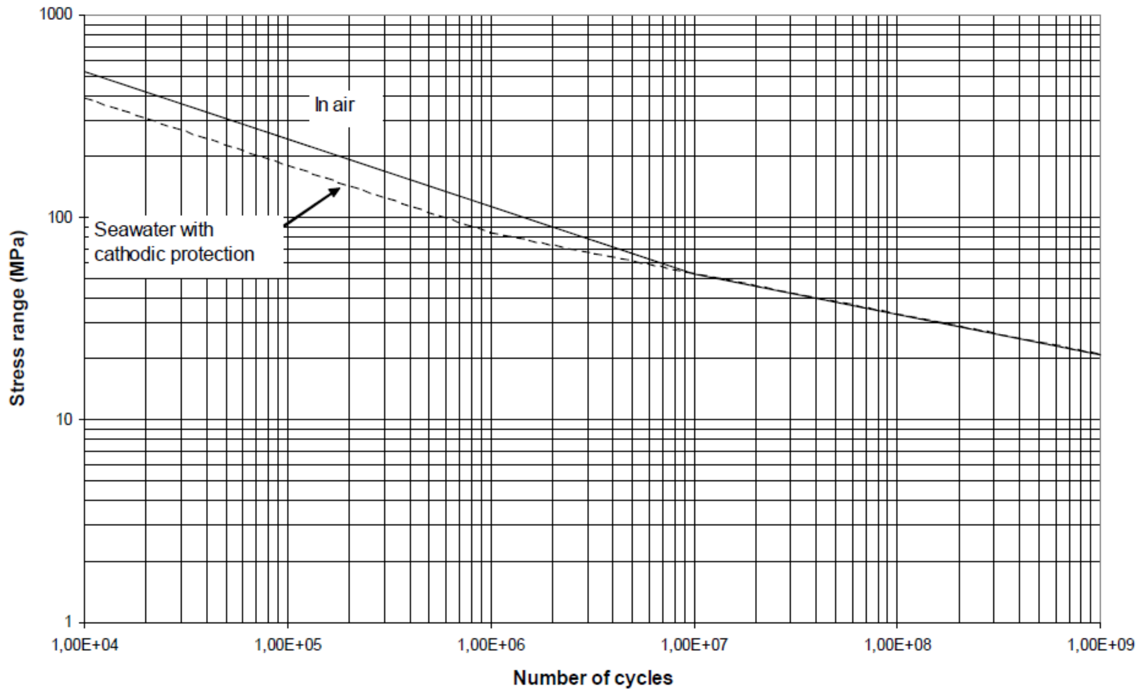


Figure 18 S-N Curves for tubular joints in seawater with cathodic protection (DNV-RP-C203, 2010)

2.3.4. Inspection

Any load large enough to trigger fatigue of the riser need to be taken into account:

- First-order wave effect
- Second-order vessel motion
- Vortex-induced vibration
- Thermal and stress induced stress cycles

For the fatigue life calculation all kind of load effects should be considered, even temporary conditions like hang off and running modes as well.

ISO 13628 - 7, section 6.4.9 states that design fatigue factor 3 ($D_F = 3$) should be used for the calculated fatigue life if the components that can be inspected otherwise design fatigue factor 10 should be used. If the component can be inspected, the inspection interval should be at most one-tenth of the calculated fatigue life. The standard also states that it is suggested to use cumulative fatigue damage due to its simplicity for assessing fatigue life of component and crack growth model can be also used for determining NDT methods during fabrication and for inspection planning.

Initially, SN model can be used to determine inspection intervals and it is also assumed that no fatigue cracks will be detected during inspection and it will be send for further service with the same inspection interval. In case of crack detection the riser joint might be discarded or repaired and send for further service, though inspection interval need to be reassessed.

2.4. Riser Monitoring System

Riser monitoring system is a new type of the operation monitoring system which designed to ensure integrity of the equipment and operation, in other words it ensures that vessel operates in safe operational window and equipment on riser stack utilized properly by measuring riser state parameters. Riser monitoring system alongside with GRA can benefit during the operation and can be used for inspection/maintenance planning.

There are number of benefits from the riser measurement system

- Supports real-time decision making
- Better understanding operation
- Larger operational window, because result based on analysis are bit conservative
- Safety of the personnel and environment
- Integrity of the equipment
- Better planning for inspection etc.

As the word "monitoring" states in the name, the system requires number of measuring sensors to measure some parameters of the operation. Alongside information from measurement need to be transported to topside, received signals should be interpreted and presented in a proper way to the operator. Therefore riser monitoring system as minimum should include:

- Sensors for measurement:
    - Acceleration: accelerometer.
    - Angular rate: gyroscopes.
    - Inclination: inclinometer.
    - Tension and bending: strain gauges, displacement sensors, Fiber Bragg Grating.
    - Curvature: curvature sensors.
- Communication technology
    - Hardwire: data communicates by cables.
    - Acoustic: data communication goes by acoustic system.
    - Standalone: data saved to internal memory and retrieved after operation.
- Micro-electronic technology
- Softwares
- Materials underwater electrical system (An, 2009).

FMC is not pioneer in implementing riser monitoring system, there are other companies on the market who provide analog services. Here in this chapter some of them are described with their products and with product description.

FMC Technologies

The system for FMC is still under research and development stage, though the company preparing new system for Statoil and Chevron. The system called Well Access Management System (WAMS), and FMC has already conducted couple of successful testing and offshore measurements on Kirinskoye oil field in Russia for verification of the system.

Architecture of the WAMS consists of core and advisory parts. Core part of the system gives bare data of the measurements and presents it to the operator. Beside the data from measurement some additional information about state of the measuring equipment and list of the utilized equipment can be given. The advisory part of the system is like a brain of the system which can advise for operation, make some calculation regarding state of the riser joints and predict future loads.

- Core part of the system consist:
    - strain gauges
    - inclinometers

- Fiber optic cables
- Processing Computers

- Advisory part of the system consist
  - Operational Limitation function.
  - Calculation of the utilization of the main stress joints.
  - Forecast operation

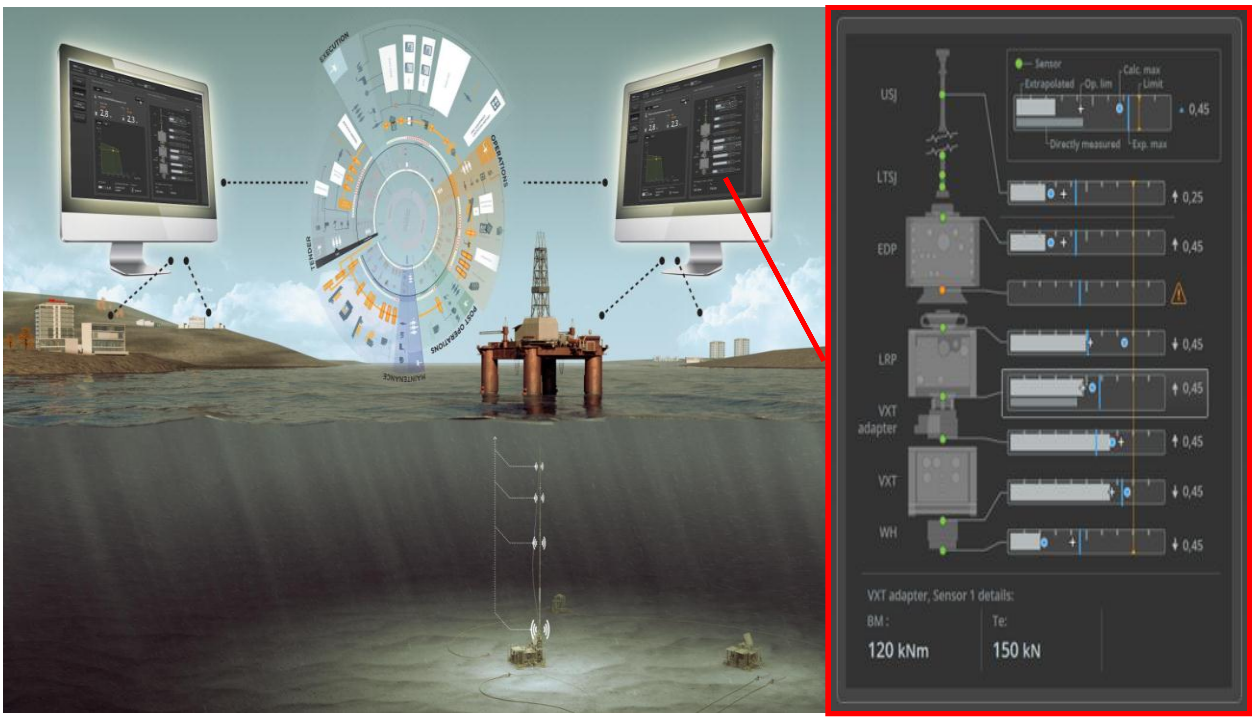


Figure 19 FMC's well access management system (FMCTI, 2013)

The Figure 19 shows the general life cycle process of the WAMS and snapshot from advisory part of the Human Machine Interface.

2H offshore and Pulse

2H offshore and Pulse is one of the pioneers on the riser monitoring system. They have very wide variety of sensor packages regarding. 2H Offshore's monitoring system can be flexible and can be implemented not only in WO or marine risers, but also mooring systems as well. The 2H offshore is responsible for advisory part of the system whereas Pulse is responsible for measurement system with their sensors (Pulse, 2014).

The architecture of the system might consist either standalone, hardwired or acoustic communication system, and can be implemented in different scale (Maheshwari, Ruf, & Walters, 2008). For example in the Figure 20 typical illustration of monitoring system is shown with sensors. This particular system is more dedicated for wellhead fatigue monitoring and that is the reason for using the motion sensors on lower stack of the riser, although if vortex induced vibration (VIV) is on concern the several motion loggers can be implemented along the riser length for better monitoring.

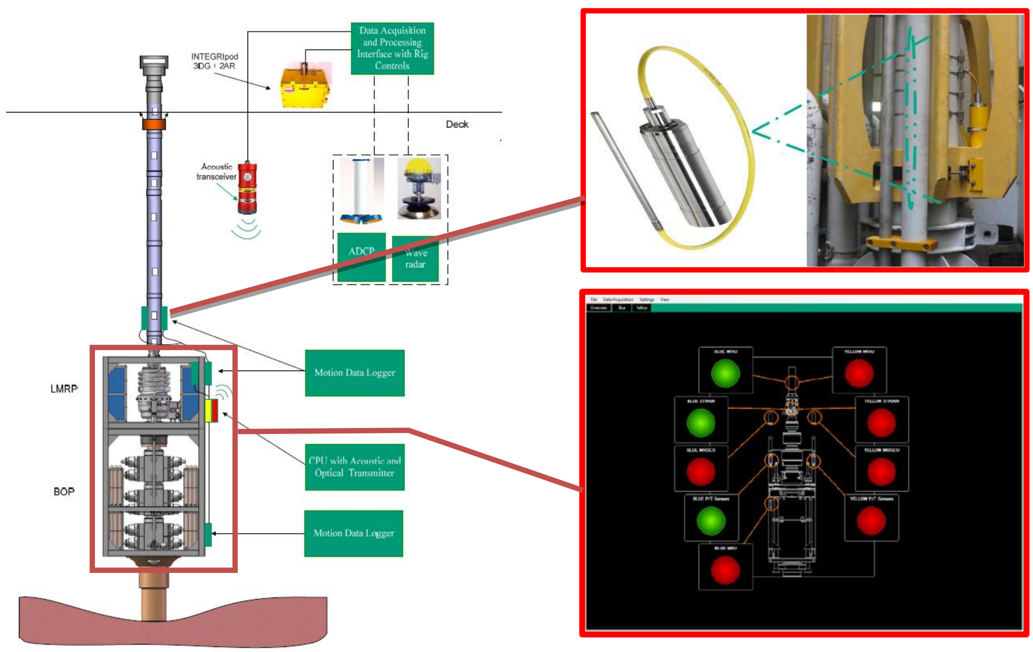


Figure 20 Typical illustration of 2H offshore's RMS (Ruf & Diestler, 2014)

The company offers package with set of modules for drilling riser integrity management. The package is called DrillAssure, which is monitoring system for drilling risers; the package may come with several software modules as (Pulse, 2014):

- DrillJoint: Stack-up calculation, Riser inventory and usage, maintenance tracking.
- DrillAdvise: Real-time operational advice, vessel position optimization, time to go.
- DrillWindow: Pre-drilling Global riser analysis
- DrillFatigue: Wellhead, conductor fatigue tracking system based on displacement and movement.
- DrillTransit: Optimization of well transit speed and LMRP integrity management.
- DrillVIV: VIV fatigue calculation module.

Kongsberg Oil and Gas Technologies (KOGT)

KOGT Riser Management System has been developing since late 90's, in the beginning system used to be just an advisory system based on GRA results and measured riser fatigue during operation by look-up tables. Right now system has undergone vast developments and consists of several sensors, which can be integrated with Enterprise Content Management (ECM) system and can be implemented with operational advisory packages (Hugo & Berge, 2011). The system can be used for both open sea mode and in-riser mode riser system.

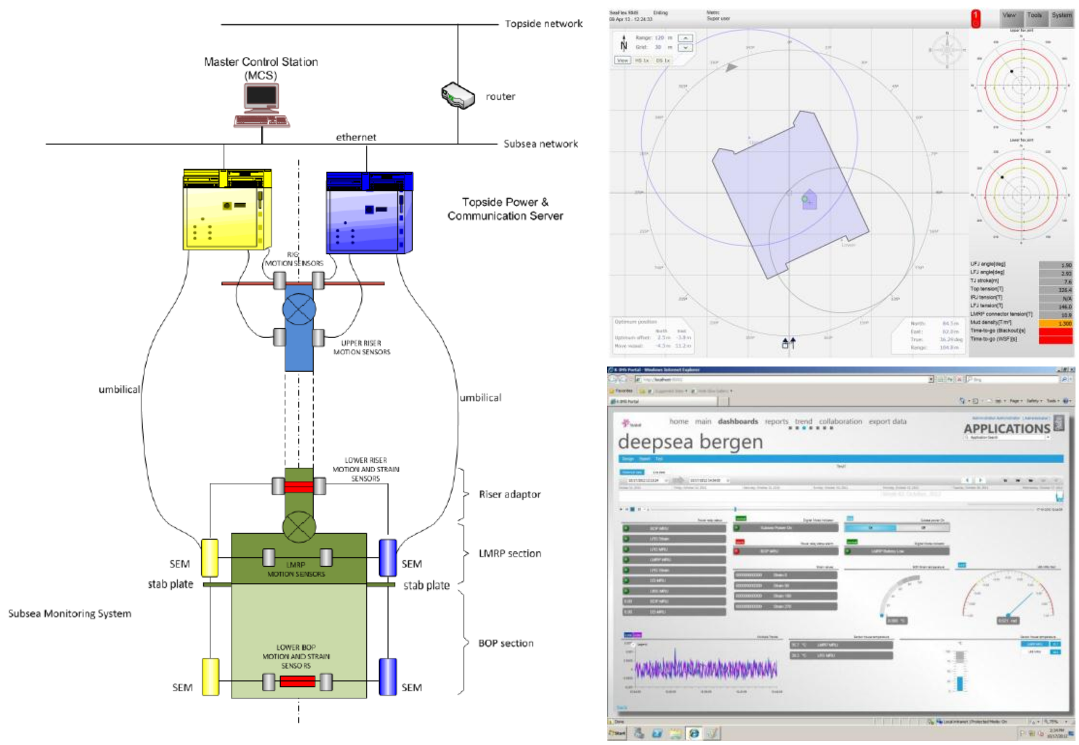


Figure 21 KOGT's RMS architecture and GUI screenshots (Jensen G. , 2013)

Architecture of this system consists of 7 sensors with redundancies (Jensen G. , 2013).

- Strain sensors:
  - Bottom of BOP.
  - LMRP above the flex joint.
- Motion Sensors:
  - Bottom of BOP
  - Just under the flex-joint

- Just above the flex-joint
- Just under the upper flex-joint
- Just above the upper flex-joint

In the Figure 21 the architecture and some screenshots from the system's software are shown. The system enables to show the critical parameters during operation, give state of the riser system, vessel position can be optimized in order to avoid risk of damage, fatigue on critical components can be tracked. System works by integrating data from vessel, sensors and environment. Again it is possible to integrate system with ECM system (e.g SAP), so all the information regarding tally can be read and written there.

Optima

The system based on FEA tool, the tool was developed by MCS Kenny. The software tool has an advanced 3D capability. The system eneables:

- Show operational window
- Advice optimum position and top tension range.
- Hang-off, running and retrieval operations
- Drift-off analysis
- Fatigue tracking of riser joints
- Monitor VIV response
- Shows stress ranges on for individual joints.

For the analysis the following the information required:

- Vessel position and heading
- Tensions on tensioners
- Current profile and sea state.
- Internal pressure
- Mud weight etc.

In the Figure 22 typical illustration of MCS system can be seen, where system consists three Acoustic Doppler Current Profilers (ADCP) in order to determine current profile. The figure also illustrates the screenshot of operational window and riser management tool (Schluter, 2009).

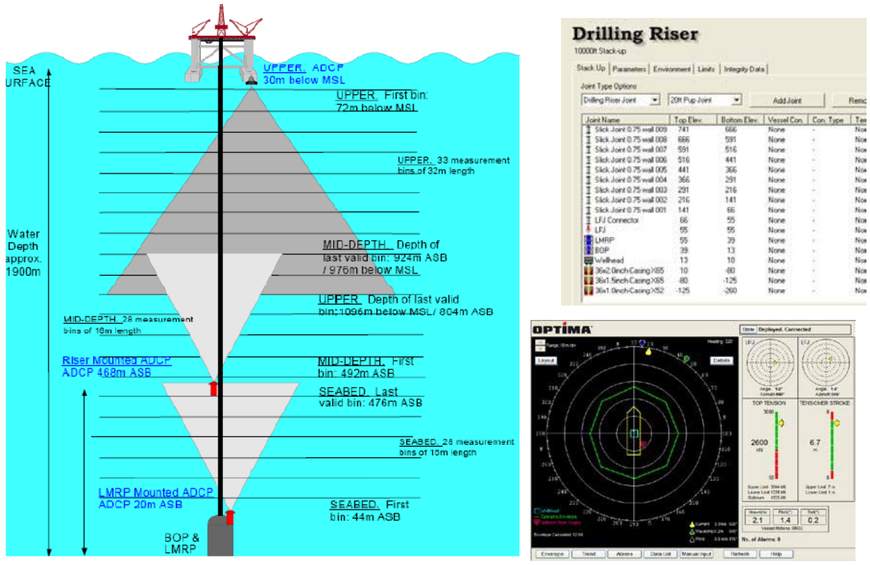


Figure 22 MCS Riser management system (Schluter, 2009)

Japan Agency for Marine-Earth Science and Technology (JAMSTEC)

The system was designed by the company Stress Engineering for JAMSTEC in order to track fatigue usage of the marine riser in drilling operation. Therefore system is called Riser Fatigue Monitoring System (RFMS).

Architecture of RFMS was designed for measuring fatigue due to VIV, and the system was used on the cost of Japan on the depth around 2000m. The system consists of several Subsea Vibration Data Loggers (SVDL) along the length of the riser stack. The SVDL's communicate with the topside system by fiber optic cables which allow sending real-time values of three directional transient velocities and two angular velocities of the riser. The data acquired from the sensors used for calculation of the stress along the risers, engine of this calculation is based on FEA tool where Modal Decomposition and Reconstruction Method is used for modeling vibration response of the riser. The Figure 23 shows the architecture of the system. On the left-hand side of the figure is shown the vessel with marine riser and installed locations of SVDL, on the right-hand side top shown the picture of SVDL. Whereas on bottom the figure the cumulative maximum fatigue on riser along the length with values are shown on different directions (Mcneill & Saruhashi, 2013).

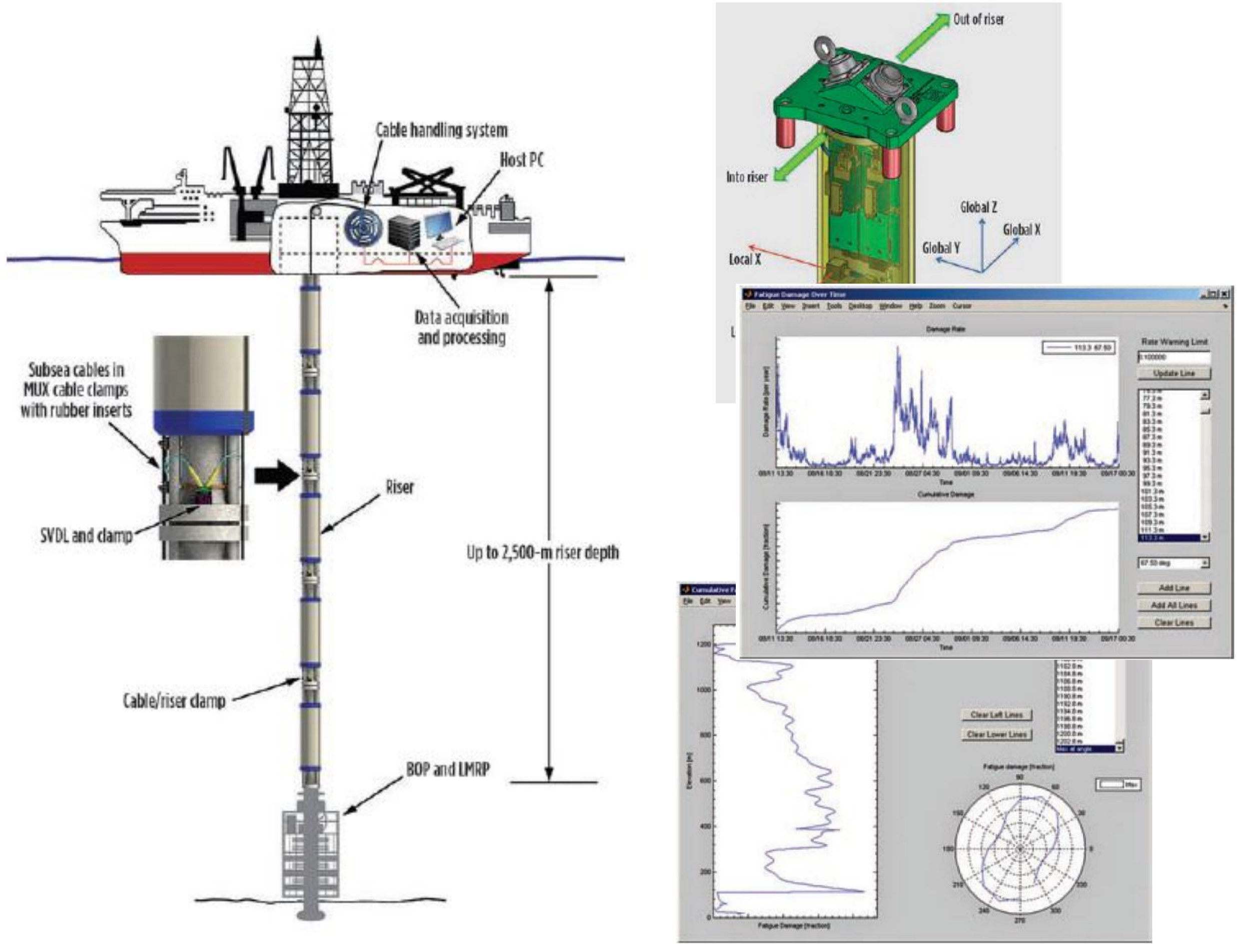


Figure 23 Illustration of the JAMSTEC's RFMS (Mcneill & Saruhashi, 2013)

For other types of risers

Riser monitoring system can be also implemented for flexible risers as well. Water ingression, fatigue on wires, high temperature and other factor can cause the failure of flexible risers.

NOV has implemented riser monitoring system for flexible riser to monitor following features:

- Stress; monitored in selected cross section by Fiber Bragg Gratings (FBG).
- Temperature monitoring throughout the length of riser: by FBG
- Water ingress monitoring into annulus

Some other techniques based on energy release method. Acoustic Emission Sensors (AES) mounted on the riser detect fatigue energy release during wire rupture. This technique detects abnormal energy effects on riser and by using breaking index the number of ruptured wires and locations can be determined. (Mistras, 2012)

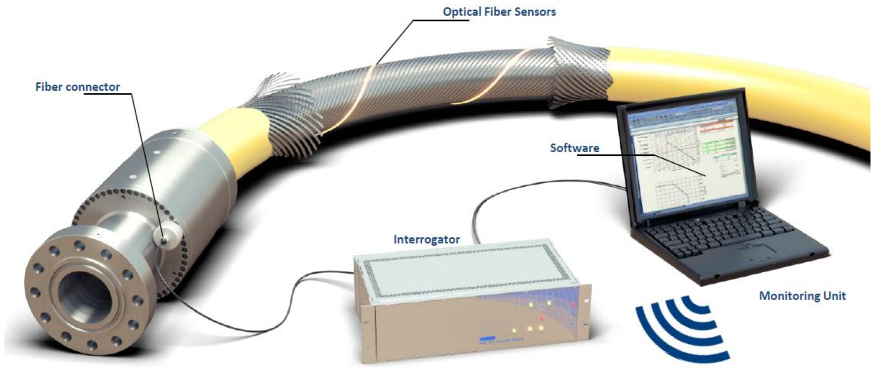


Figure 24 Flexible riser monitoring system (Dahl, 2013)

Riser-Anchor Monitoring System (RAMS) is used to monitor positions of the mooring lines and riser underneath the Floating Production Units (FPU), the system uses Sonar head deployed just between the mooring lines or close to risers under the water. Main advance of the system it can be deployed apart from moving parts and provides real-time data, which can be used for further analysis. (Tritech, 2014)

Radiographic inspection technology is used to find failures in flexible riser like: wire cracking/breaking, wall thickness reduction due to corrosion, buckling and unlocking of pressure armor. Gamma isotope holder and flexible riser robot crawler used for detector. By going through the riser length the radiographic image of the riser will be taken and analyzed afterwards (Sood, 2014).

Magnetic inspection methods also can be used for the riser condition monitoring system, for instance Innospection's MEC-FIT technology uses ROV based tool which can detect cracks along the riser (Innospection, 2013). Another example is MAPS-FR's tool for detection of wire rupture also based on magnetic field. The stress values on the riser's wires can be detected by magnetic field, so the wire ruptures up to 30m away from location of MAPS (Figure 25) can be detected. (Buttle, 2012)

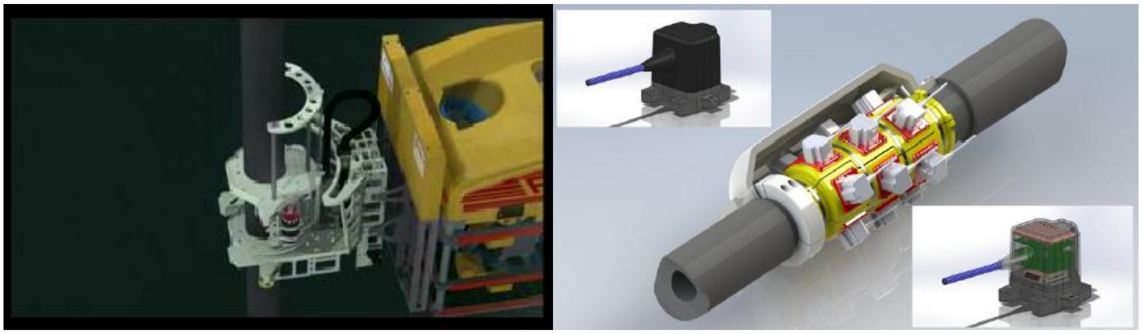


Figure 25 MEC-FIT Technology and MAPS-FR (Innospection, 2013)

There are also number of other monitoring techniques used in other industries like in aerospace or railways industries, but due to limited size of the thesis they have not been included and by the same reason only short descriptions is given for before mentioned monitoring methods. But author in the coming chapter adopted some of the techniques to suggest for new riser management system. The more detailed description of this system will be given in following chapter.

3. Methodology for riser management

The section provides information regarding Riser Management System (RMS) process. The process encompass whole life cycle of riser systems. Illustration of the process is shown in the Figure 26.

The RMS process contains four main modules as:

- Preparation
- Maintenance Planning and Execution
- Operation and Maintenance
- Evaluation

Each of the modules consists of sub-modules and steps. All this steps and sub-models work towards system integrity. The steps and sub-models have some common information which can be shared between each other. The author suggests using common database or Enterprise Content Management (ECM) to have a track in decision making process and ease information sharing.

Figure 26 Riser management system

3.1. Prepare

RMS has to be used to ensure operation integrity, optimal riser usage and optimal riser maintenance. To achieve better performance of the system, it should be designed in a proper way by carrying simulation or testing. The stage “prepare” is conducted to design the system for further operations.

It is easier to model system by having good knowledge about subsystem. Therefore, first component analysis should be conducted for the all risers used in a system. As it was described in the chapter 2.2, the output from component analysis (stiffness, SCF, Tension capacity etc.) is used for the GRA. Whereas information regarding operational limitation and about the weakest component (bottleneck) of the system obtained from GRA is used for component analysis in order to improve design of the limiting component. Not only result from component analysis drive the design of the component but also information regarding environment to be operated, operational requirements, local regulations, and information from previous operations plays role. All this values will be used to design equipment with optimal design. Process for the riser design optimization is shown in the Figure 14.

As it was described in a broad range in chapter 2.2 the operational window and fatigue usage for the specific operation will be obtained from GRA. This information should be stored and used during operation and for maintenance planning stage.

3.2. Plan operation and maintenance

Basic idea behind planning operation is to have designed equipment for the operation on time without any delays. Therefore, detailed procurement process should be established which ensures smooth planned execution. In this stage also preservation, storage and maintenance (PSM) actions need to be planned for the future.

The ISO 13628 - 7, section 6.4.9 states that design fatigue factor 3 ($D_F = 3$) should be used for fatigue life calculation if the components can be inspected otherwise design fatigue factor 10 should be used. If the component can be inspected the inspection interval should be at most one-tenth of the calculated fatigue life. There are two ways to measure actual fatigue life of the equipment:

- Based on global riser analyses (Risk based maintenance/inspection)
- Based on actual monitoring (Condition based maintenance/inspection)

The global riser analysis believes to give conservative results than actual measurements, because probabilistic model used for the calculation. Benefits of using GRA report is low cost for implementation because of hardware absence for measurement. The author suggests logging environmental data as wave height and vessel drift during the operation to narrow uncertainties in the calculation fatigue life of the equipment.

The riser monitoring system is considered to be state of the art in riser maintenance, there is not many operating companies practicing it. Compared to traditional methods, riser monitoring gives more accurate results. Actual measurement allow for better inspection planning, inventory management and prolong the life of the key components by advising optimal rig position and top-tension etc. Since the thesis dedicated for condition based maintenance (CBM) for well access system, more detailed description for riser monitoring system establishment guideline will be given below.

Based on the study of standards ISO 17358, 13381-1, 13379 regarding condition monitoring procedures the following methodology (Figure 26) is created.

The methodology consists of five consequent modules (Figure 26):

- System classification
- Measurement
- Data Acquisition and Processing
- Prognosis and Diagnosis
- Advisory Generation

Each of these modules can be divided into several steps. The steps define the design and implementation of the riser monitoring system for maintenance, operation optimization and operation planning. Description for the step for the guideline given below.

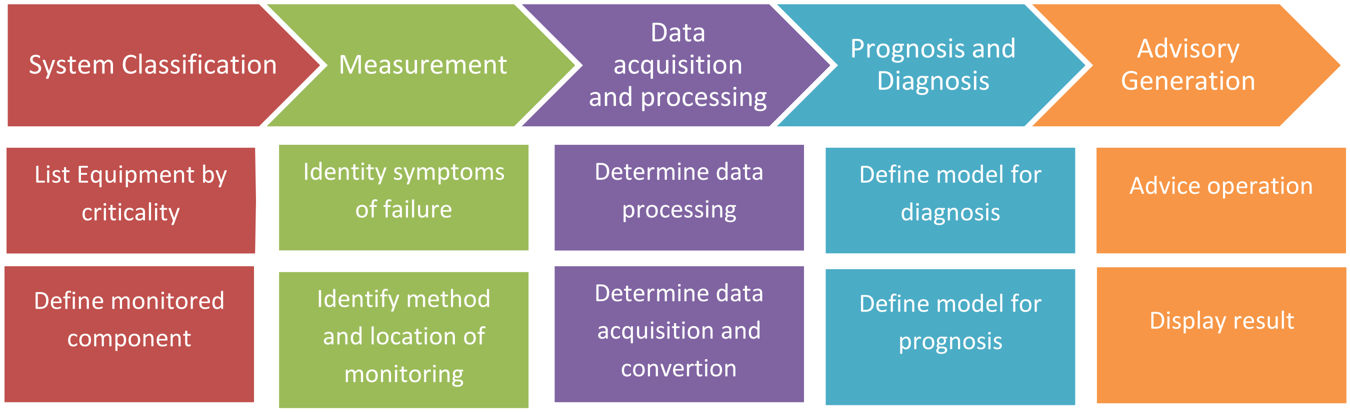


Figure 27 Riser monitoring system definition process

Ranking of equipment based on criticality

As it was described in the chapter 2.1 there is a range of well access system equipment used in the intervention operations. Implementation of riser monitoring is expensive, so in order to minimize cost only critical equipments can be monitored during operation. First of all, all the equipment in WAS needs to be listed and ranked by the criticality. Criticality ranking can be found by doing failure modes, effects and criticality analysis (FMECA). There are several standards which give guidelines for conducting FMECA as BS 5760-5, IEC 60812 or SAE J1739. The FMECA analysis can be based on the steps shown in the Figure 28, whereas for the system all probable failure modes and consequences of the failures are defined, and this input will be used to determine criticality of the each riser joint.

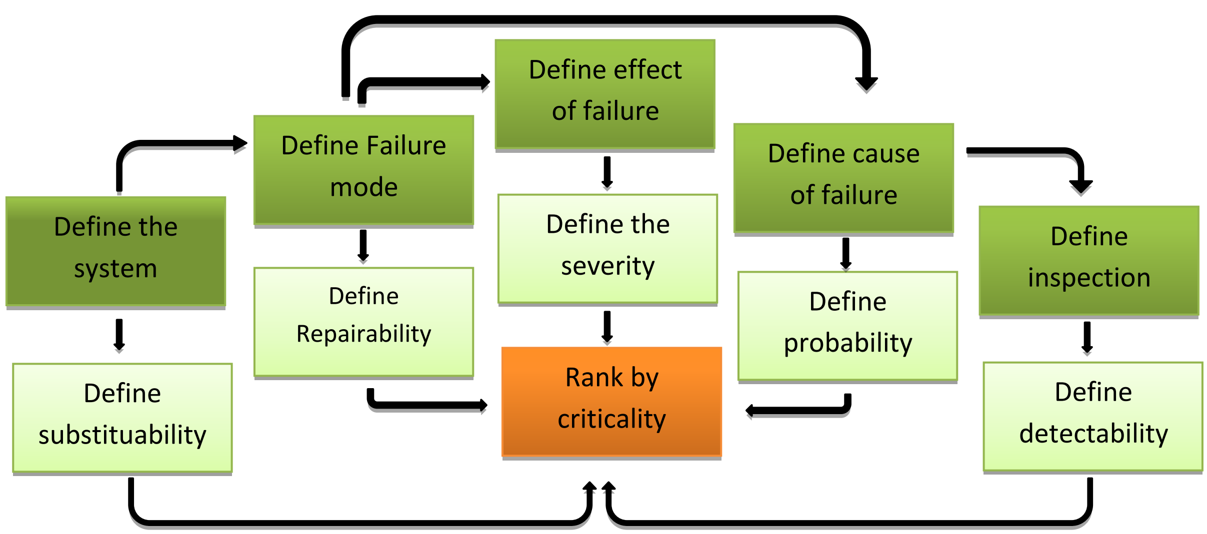


Figure 28 FMECA steps

While system is defining it is possible to know which equipment can be substituted and which not, for instance if failure happens on weak-link then it can be replaced whereas wellhead not. The second type and degree of failure defines either equipment can be repaired or not. For instance small fatigue cracks can be repaired by grinding but not buckling. By the same way failure effect, cause and inspection define severity, probability and detectability of the failure respectively.

Determine equipment to be monitored

In this step potential equipment for the monitoring should be determined. A selection criterion is mainly based on FMECA analysis and equipment with high criticality ranking should be in the interest. However, not all equipment with high criticality ranking can be monitored, because of feasibility issues or technology gap.

Failure symptom identification

The study is done with the purpose of determining main attributes for monitoring. Detection or prediction the failure of component is all about ability to detect symptoms. Based on FMECA analysis all failure modes have to be studied for symptom determination. Usually failure mode and symptoms analysis (FMSA) is conducted in order to find related symptoms for each failure modes. As an example, the symptoms as high stress or strain on riser's cross section causes riser buckling or over yielding. Failure modes is not always has direct symptom for failure, for instance, fatigue or corrosion for permanent subsea equipment one of the failure modes where ambiguous numerous symptoms can be listed. Cutting edge analysis tools or special techniques might be required to determine state and prognosis the failure.

Identify method of monitoring

Vast number of monitoring techniques is used in riser monitoring system. A list of the monitoring techniques needs to be generated for each predefined failure symptoms. It is also recommended to map each failure symptoms for monitoring techniques for detection. The information from the map can be used during method selection, whereas parameters like performance, cost and size of the method should be considered.

There are some failure modes which cannot be measured directly, though indirect measurement techniques can be used for identification of the state of the equipment. For instance during operation/production phase it is not possible to monitor/measure the corrosion inside choke valve on X-mas trees, but the information regarding changes of flowrate, shift of the choke valve position, pressure difference across the corroded part of equipment can indicate the corrosion problem (Bencomo, 2012).

The frequency of monitoring is also need to be defined in this stage. Monitoring of weather parameters like significant wave height might be done each 10 minute, though other parametes like vessel offset or inner pressure need to be monitored more frequently. In the Figure 29 we can see how sampling frequency is important for the strain measurement, whereas stress range defines the fatigue life of the riser joints. Risers have more dynamic nature rather than vessel so more frequent measurement require for this case. The exact frequency of measurements has to be calculated based on GRA and accuracy level required for the monitoring.

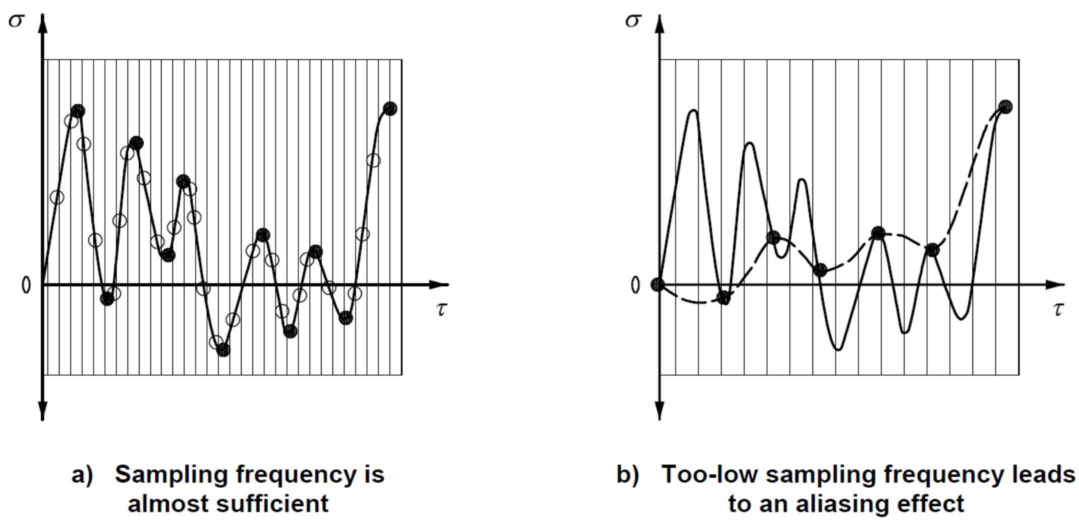


Figure 29 Example of sampling frequencies for finding fatigue damage (ISO-13628-7, 2006)

Identify location to be monitored

Not only right monitoring technology is important for the accuracy but also location of implementation also plays a role. Depending on system architecture, sometimes it is possible to install special sensor in a location to measure actual equipments and neighboring equipments parameters. However, sometimes installation place parameters like size, depth, or challenges regarding power supply and data connection might limit the direct installation of the sensor on desired location.

If the intended measuring location is not feasible then other ways or locations for measurement need to be evaluated. For instance, for temperature measurement inside the riser it is not necessary to put thermometer inner side of the riser, though by knowing temperature of outer part of riser it is possible to calculate inner temperature based on wall thickness, material properties and environmental parameters, or other example; it is not always possible to install measuring tool to wellhead or conductor, then load measurement need to be taken from closest possible riser stack and the result can to be extrapolated (Otávio B.C.V, 2013).

Finally in order to choose right technique and location a Monitoring Priority Number (MPN) can be used in order to give priority for one of the several monitoring options. The MPN based on following characteristics of failure:

- Delectability - De
- Ability to prognoses - Pr
- Ability to diagnoses - Di
- Criticality - Co

Based on ranking of above mentioned characteristics of failure, the numeric values will be given to the each of them. The MPN can be found as multiplication of all of them (Bencomo, 2012).

$$MPN = De \times Pr \times Di \times Co$$

The method with highest MPN number will be preferable monitoring technique.

The numeric values describing failure characteristics are given in the Table 1. Where each of the characteristics of failure ranked based on probability of detection, prognoses and diagnoses and severity of failure. If we have more measuring methods with similar characteristics the preference can be given to the one with lower operational and capital cost, which has less complexity in terms of installation and execution. The values on the table are only limited by 5, for more complex system with high number of monitoring options, introduction of more precise and broad numeric values are recommended.

Table 1 Numeric values of used for MPN calculation

Numeric values	Detection Confidence	Prognosis Confidence	Diagnosis Confidence	Severity of Failure
1	Remote	Remote	Remote	Neglectable
2	Low	Low	Low	Low
3	Moderate	Moderate	Moderate	Moderate
4	High	High	High	High
5	Certain	Certain	Certain	

Data acquisition

Data acquisition can be done through hardware connection (for instance: fiber optic cables), acoustic data transmitters or standalone solution. Each solution has its pros and cons. The main advantages of the hardwired solution are real-time monitoring, wide bandwidth data transmission, high noise immune, although there are difficulties in terms of installation, has complicated interfaces toward subsea and topside nodes and there is high probability that it can be damaged during operation or installation (Ruf & Diestler, 2014).

In the acoustic method of data transmission the data collection is conducted by the underwater acoustic communication tool. Compared to previous method the acoustic can be categorized as semi-real time monitoring with limited bandwidth, main disadvantage of the method it has a prone to underwater noise though it is with easier interfaces and does not require much effort for installation (WFS, 2013).

The standalone solution does not have connection with topside equipment, the only way of retrieving data is to physically retrieve the memory stick under the water. The main dominances of the standalone solution are reliability of the equipment, requires minimal installation effort, has minimal interfaces toward other equipment and cost competitive, nevertheless it does not give any real-time information and that is why cannot be used for real-time decision making (Ruf & Diestler, 2014).

The real-time data acquisition requires special software and devices. In case of acoustic method of communication just under the sea surface the special receiver is placed for receiving signals. The devices or software packages also required to digitalize the measured values, for instance, in case of Fiber Bragg Grating to measure temperature and strain the software package for signal processing and photo detector is required to detect reflected wave length and relate it to actual value either strain or temperature (Pan & Chen, 2010).

The received information need to be logged in a right form and saved with correct tag name (address or identification of the signal), values, information regarding quality and timestamp.

Data Processing

The information given in digits does not mean anything unless it is not converted into relevant description. For instance, strain received into the system can be given in some numbers, but it needs to be converted into normal strain values, effect of temperature and pressure also need to be considered and compensated by some meaningful pretested algorithms, after all the strain can be transformed into loads like bending moment or tension on special section of the riser joint (Maheshwari, Ruf, & Walters, 2008). The data can be used to estimate some other values, for instance load on wellhead and conductor. Redundancies also need to be considered on to the system, for example the failure on one sensor should not affect the result generation. Data filtering techniques also can be used in order to get right data and to simplify calculations.

Prognosis and Diagnosis

In order to diagnose or prognoses the failure in the system baseline for the operation need to be predefined. For the parameters lying outside the range of the baseline, the system needs to report abnormality and trigger alert or alarm. The warning system can be categorized as faults, alarms and alerts.

Fault in the system first level of warning type basically given to the operator to show that something wrong happened with equipment. Fault mainly does not give any danger to the system, but it may lead to some unpleasant outcomes like: loss of data logging, sudden damage in one strain gauge etc.

Alert warning will be shown if some component of the system requires some maintenance action or need to be replaced. If the power supply for the system is quite low it means the power support needed otherwise the system might not function as intended. Alarm is generated in a point when the system cannot operate in current state or if operation is going lead to catastrophic consequences. The example can be excessive yielding of the riser joint during operation, then alarm will rise and operator can reposition the vessel to reduce bending moment on it.

In any point of operation the system should show the state of the critical components configured for the measurement. Though result from pre-operational GRA can give rough estimated state of the each single component on riser joint in any point of the operation, but as it is better to rely on real measured data for critical components. Limiting component on the system can be any of the components depending on structure of riser system and sea state.

Diagnosis for the equipment can be done in order to determine current condition of the equipment or to determine any faults and failure on the system. At least the location of the failure, type of the failure and the time of occurrence need to be mapped during diagnosing (Isermann, 2006).

All the parameters causing failure of component or system in diagnosis need to be taken in consideration, and sometimes combination of effects can accelerate the process. As an example the combination internal overpressure, bending moment and tension can increase the utilization of the riser joint during operation. Therefore, increase in inner pressure will lead to decrease of bending moment and tension capacity of the component.

In order to plan for maintenance a Remaining Service Life (RSL) need to be found before. The way of finding RSL is called prognoses. Main prerequisite for the prognosis methodology is presence of progressive degradation characteristics on component otherwise the implementation of the prognoses methodology can be quite challenging. For instance the failure due to fatigue can be categorized as progressive degradation, because for instance S-N curve gives the number of safe cycles under certain stress range, so information about used cycles and total number of cycles can be used to determine remaining number of cycles before it is expected to get any fatigue crack.

Process for this methodology can be divided into four parts (ISO/FDIS-13381-1, 2004):

- Pre-processing
  - When the all failure modes need to be defined and based on FMSA analysis.
  - Event and alarm, and other notification scenarios need to be defined as well
- Prognosis of failure modes detected
  - Assessment severity of the failure has to be carried

    - Assessment of expected time to failure has to be carried
    - Defining critical component etc.
- Prognosis of future failure modes
    - Assessment of consequence failure modes triggered by one failure
    - Assessment of remaining time to the failure.
- Post action prognosis
    - Maintenance planning based on information above
    - Generation new prognoses after maintenance action

Advisory module

Main purpose to have advisory module is to be able to give decisive information to the operator. Information can be used for real-time decision making, or it can be used in order to plan for future maintenance actions. For instance, only the information about remaining fatigue life of each joint can be used to plan for operation, maintenance, and advice for optimal position in order to prolong the life of the critical equipment and so on.

Demonstration of the system

All the important information regarding the operation has to be shown to the operator all over the process. The information can be about:

- State of the each individual component
- Alarm, alerts, fault generated during operation
- State of the monitoring system
- Maintenance and operation advisories
- Tally advisory for the operation (riser's needed for operation in part number level)
- Simulation of the future operation
- Operation planning module
- Prediction of the equipment usage for future operation etc.

All the information in the module need to be given in coherent form so it can be easily caught and understood, besides recommended actions also need to be displayed. Typical display of the advisory module for FMC's WAMS is shown in the Figure 30.

Figure 30 Display of FMC's WAMS module

3.3. Operation and Maintenance

The crucial factor during the operation is the safety of operation and integrity of the equipment. In this stage operation should be carried out by guidance of riser monitoring system (for instance: by using advisory module) and by using GRA report for operational window. During the operation an important operational parameters like vessel position and weather condition should be monitored. If required, periodic or other inspection should be carried out during operation. There are some operational and preoperational procedures for follow up like testing during rigging down, calibration of measurement sensors so on. Operations should be carried out within operational window, whereas typical illustration of operational limitation shown in the Figure 31.

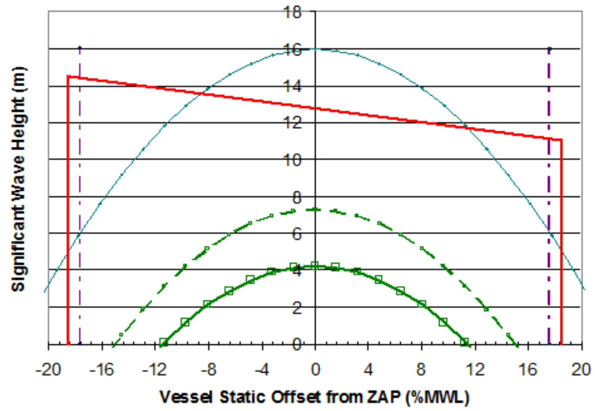


Figure 31 Typical illustration of operational window

3.4. Evaluate

These stages are called post-operational analysis, in this stage the data from offshore operation either physically or through internet need to be transported to common database (SAP) and analyzed. The result from analysis has to be used as a feedback and should be used for equipment maintenance and for system design optimization. Activities performed in "Evaluate" stage:

- Make sure that data was transferred correctly to common database (SAP)
- Make sure the data has right link for component or activities
- Analyze the data in the system and generate report
- Link the result of the report for relevant component or operation
- If there is any bottleneck in the system suggest for improvement/redesign
- Advise for maintenance or inventory

4. Case Study

In this chapter implementation of riser monitoring system is shown by using case study. Since the scope of the thesis dedicated for riser monitoring system, the chapter mainly will show implementation of riser monitoring system and give an overview for the RMS.

The chapter divided into two subchapters:

- Defining riser management system
- Defining riser monitoring system

Discussion will be carried out at the end of the chapter.

4.1. Defining riser management system

Traditionally RMS is more focused on operation, maintenance and logistics of the riser. Author suggests using integrated riser management system discussed in chapter 3, which include all the stage for the riser's life cycle. Figure 32 shows the flowchart for the RMS where all the stages for the proposed RMS and all main sub-activities illustrated. It is recommended to use ECM as a database to keep information and responsibilities. Requested information should be easy accessible in any places, i.e. onshore/offshore offices, mobile application, as it is shown at the right bottom in Figure 32. The flowchart shows that RMS is based on three main processes; analyze (data from the operation, maintenance), optimize (optimize design, system), execute (implementation of the system, improvements). These processes carried out in four stages. The description for the stages given below:

- **Prepare**: author suggests developing a tool integrated with the ECM to save all important information for the component (SCF, capacities etc.), for the operation (window, tally list etc.) in an easy form for next users. Information should be saved in a part number and operational level. Information can saved in predefined template by all user, so it can be easily interpreted by everyone.
- **Plan:** it is recommended using a tool integrated with information from the stock, so automatic mobilization planning can be done. It is suggested adding features into the tool to advice for the inspection and maintenance, for instance, when the operator gets the list

of the equipment shipped and type of the operation, they should automatically get a report about how they should handle the equipment and maintain it and so on.

- **Operate:** during the operation riser monitoring system will be used for the guidance along with GRA report. The riser monitoring system (e.g. by using sensors and other measuring tools) gives better understanding for the operator about the state and usage of the riser components. The inspection and maintenance activities should be based on the measurements. Therefore it is recommended to implement features for the riser monitoring system which can propose for inspection and for the positioning of the vessel etc. All information during the operation should be saved in ECM by online communication and should give same surveillance capabilities to onshore personnel. For instance onshore personnel should be also able to access the same information what operator in offshore has.
- **Evaluate:** in this stage the analysis of the data from the operation will be carried out. The analysis should be carried out by the same competence or by same people who is responsible for prepare stage. The main reason for this stage is to learn from the experience, use the knowledge from operation and better understand the system.

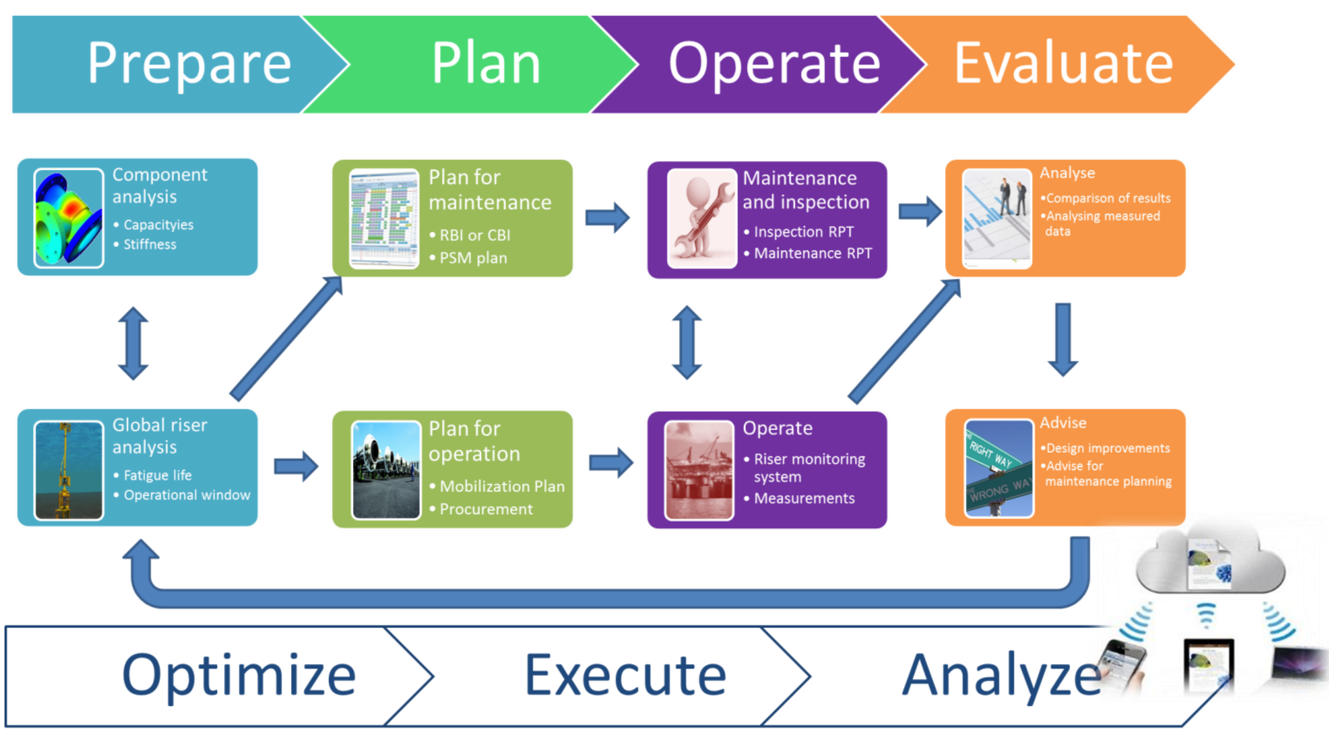


Figure 32 Illustration of RMS to ECM integration

4.2. Defining riser monitoring system

In the main part of the paper, methodology for implementation of riser monitoring system was generated. To illustrate use of the methodology the following case study was conducted. The Figure 27 shows the flowchart for the methodology. Stages presented in figure described below.

Ranking of equipment based on criticality

First of all, list of all riser joints used in WAMS are created (Figure 33).   Possible failure modes, and consequences of failure modes are mapped to each riser joint. Failure Mode Effect, Criticality (FMECA) analysis is conducted for some of the riser joints. The data used in FMECA is taken from internal FMC database, and some of them are dummy numbers just to show the use of FMECA. All the details regarding failure modes, and consequences, maintainability etc. are considered during analysis and the result of the analysis given in the appendix B.

Identify symptoms of failures

FMSA is carried out in order to determine symptoms for each failure mode for stress joint. As long as there is the proper preservation, storage and maintenance procedures carried during the life of the riser utiliation, the failure modes like wear, corrosion can be prevented by using periodic action. Though failures like fatigue, buckling and excessive yielding cannot be just monitored periodically. As it is described before if the fatige life of the stress joint is 100 days, then in every 10 days inspection has to be carried out in order check for crack procrack propagation should ne inspected. The main symptomes for the buckiling, yielding or fatigue are the stress range and number of cycles. The measurement of the stress range and number of cycles gives information about the actual state of the equipment.

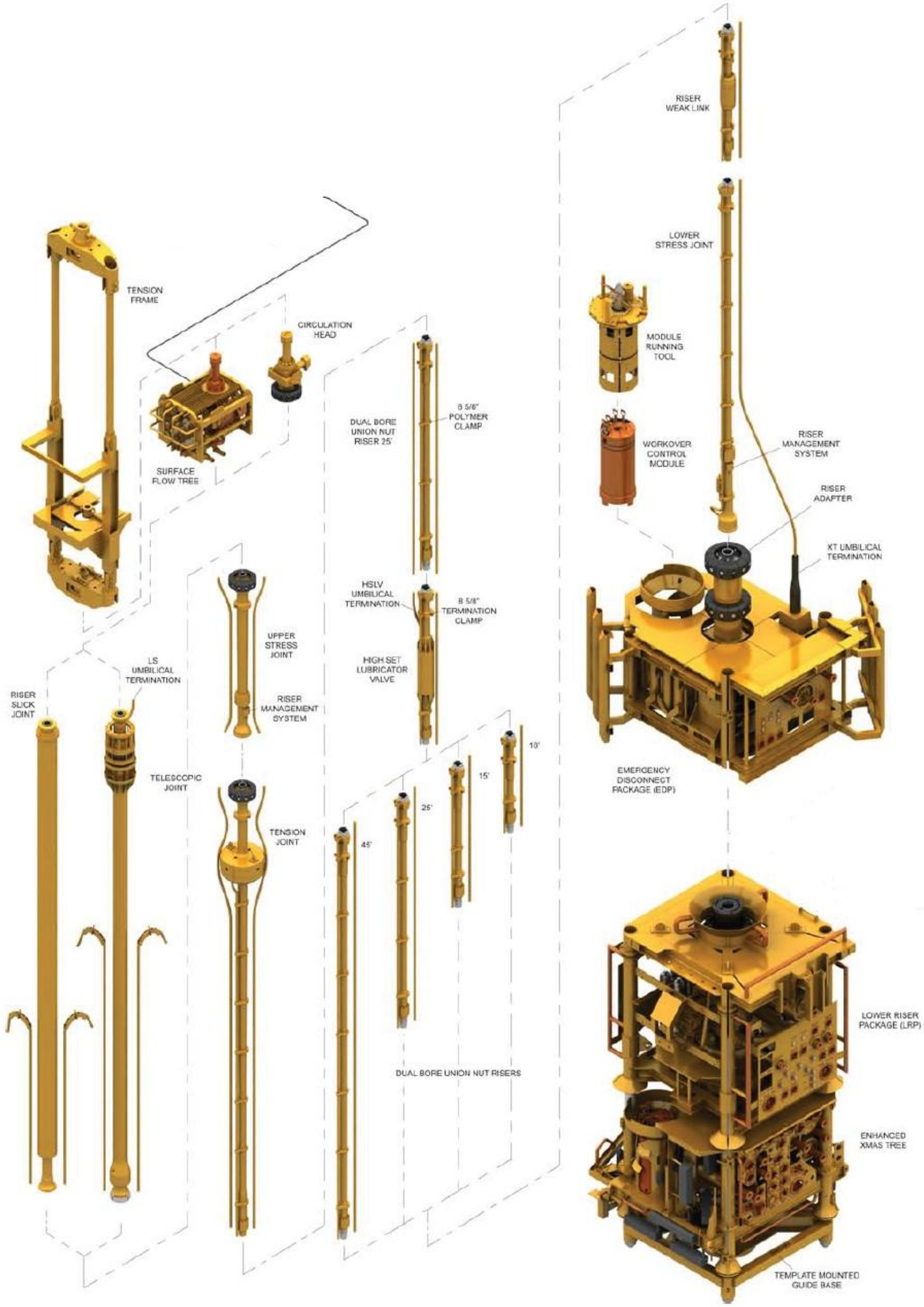


Figure 33 Completion and workover riser system (FMCTI, 2013)

Determine Equipment to be monitored

Based on FMECA, the stress joint is found to be the most critical equipment in the riser system. George, 2008 showed on his paper that the fatigue usage on riser position (Figure 34), where highest utilized components located just below seawater and just above seabed. Those a positions where upper and lower stress joints are located.

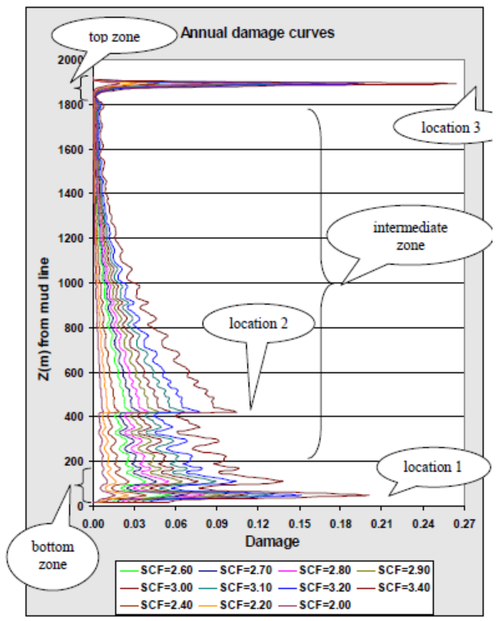


Figure 34 Damage to length graph (George, 2008)

The stress joint has different material requirement and machined differently due to stress distribution function, which escaletes price and machining time for the equipment. The other reason for being critical is number of the spare parts, for the case it is considered as only one spare part is used for the operation, some analyses showed that fatigue time for the stress joint can be as low as 100 days, then couple of monthes might be required after request before getting new one.

Identify techniques and location to monitor

Author proposes three different methods for the monitoring:

- Method 1 : Based on strain gauges
- Method 2 : Based on fatigue fuses

- Method 3 : Based on Inclinometers

Method 1

In this method, measurements are conducted by strain gauges. As the name states the strain gauges measure the value of the strain on the component which is induced by some load. Vice versa, the value of the load on the component can be found by knowing the values of the strain.

In this method author suggests to use 10 strain gauges in two cross sections of the stress joint. In first cross section five strain gauges are used, section loads like tension and bending moment are found by using four of them. The other strain gauge is used for contingency matter. The same principle is applied for other strain gauges. By knowing bending moment in the sections shear force can be found.

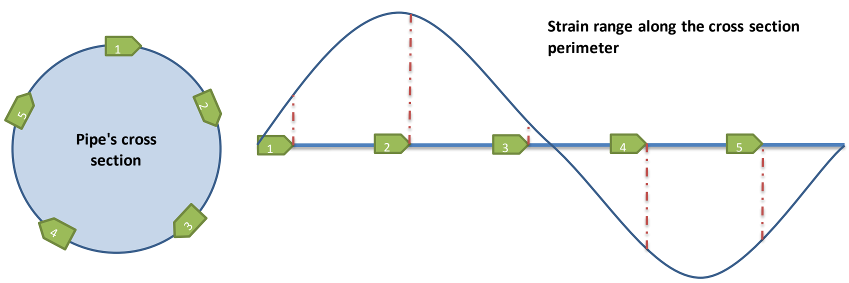


Figure 35 Strain gauges location on the stress joints cross section

Figure 35 shows the location of strain gauges on the cross section, four of them are for primary use and fifth one will be activated if one of the primary strain gauges will be out of order. One more other advantage of this method is ability to measure a load on other locations like WCP, x-mas tress or wellhead. For that simple beam theory can be used. So by knowing the load on top of the stress joint it is possible to find a load on lower stack as X-mas tree, EDP, LRP and so on.

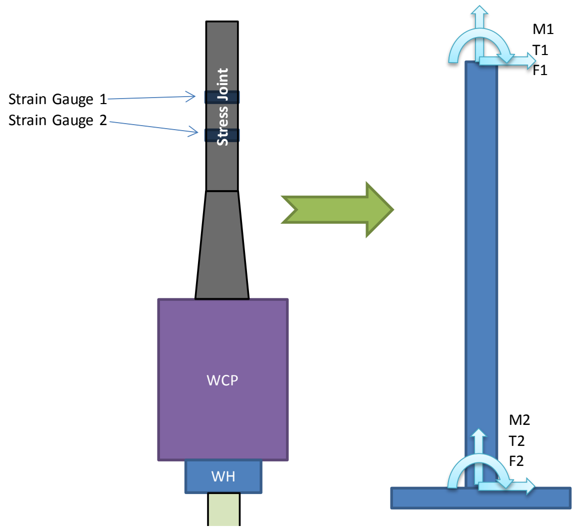


Figure 36 Load estimation on wellhead

Method 2

This method based on the use of fatigue fuses. Fatigue fuse is a piece of metal usually is manufactured by same material as riser, and has several legs with precut notches. The main principle of the fatigue fuse is to accumulate same amount of fatigue as riser. The fuses installed in a direction of riser so it can experience same loading as riser. The notches on each leg of the fuse have different size so it has different SCFs, based on this SFC the legs will fail in different order. Therefore, leg with highest SCF will fail first and it will indicate that the some percentage of fatigue life is already gone, and then second leg will fail, which indicates that riser reached other certain value of fatigue life and so on. For instance, if each leg indicated 20% of fatigue life, then failure of forth leg indicated that soon replacement or inspection on riser joint is required .The illustration of fatigue fuse on installed position is shown in the Figure 37.

Unlike method 1, in method 2 it is not possible to monitor other locations except stress joint and method is not real-time. Despite of that, the implementation of this system is less costly. The fatigue fuses can give more benefit by on permanent risers, what is needed it just periodically check it by ROV for the count of the remaining legs on each fatigue fuse.

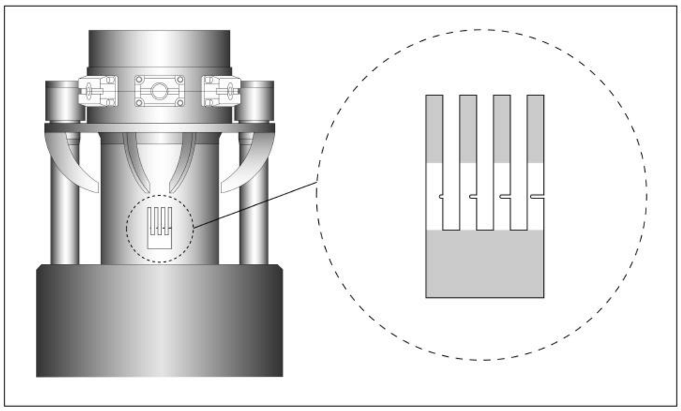


Figure 37 Fatigue fuse adhered to riser joint (Cummins, Neme, & Todd, 2000)

Method 3

This method has similar approach as method 1, but only two inclinometers will be used. Inclinometer is a device designed to measure inclination angle, rotation velocity and some of them come with acceleration measurers. Unlike strain gauges, the inclinometers does not require much effort for installation. If inclinometers can be just attached to the riser, for the strain gauges the surface of the riser needs to be prepared in a special way and during the exploitation strain gauges should be kept water free. In the Figure 38 illustration of the riser with inclinometers is shown. In this method like in the method 1 by knowing angle of inclination of the stress joint it is possible to extrapolate the load on the wellhead or x-mas tree.

Discussion

Finally third method was chosen for the concept, because :

Methods	Real-time	Accuracy	Installation	Cost	Total
1	yes	high	Difficult	High	3+3+1+1=8
2	no	medium	Medium	Low	1+2+2+3=8
3	yes	high	Easy	Medium	3+3+3+2=11

For the analysis it was considered that green gives 3 points, yellow 2 points and red one point. On the end method 3 had the highest score.

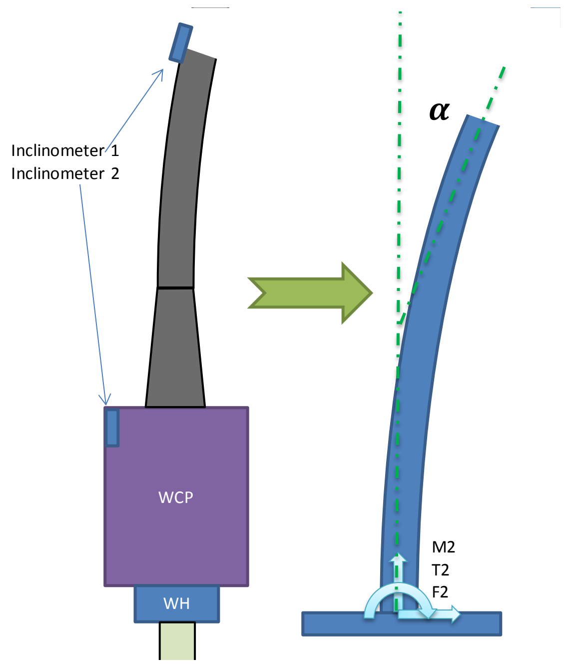


Figure 38 Illustration of riser stack with inclinometers

Data acquisition and processing

As it was described in a chapter 3.2**Error! Reference source not found.** for a given method measurement three data acquisition process exists:

- Hardwired
- Acoustic
- Standalone

All of those methods have some pros and cons. It is clear that standalone solution is not proper for real-time system. The acoustic solution is easy to implement, though, it is vulnerable for signal noise. But when there are only two inclinometers acoustic solution might fit for the source of data requirements.

The system has to digitalize the signal received by acoustic receivers and send it to topside computers. Digitalized signals have to have correct information regarding values inclination, quality of signal, time received etc. Moreover, software with angle to load transformation function need to be created. Certainly, information regarding stress joint and lower stack's mechanical properties will be required for the data processing. The software has to be configurable for the different types of the lower stack and stress joints. Values of the load calculation by the software have to be stored in database as well, with correct timestamp and with information about measured locations.

Diagnosis and prognosis

As it is described in chapter 3.2 prognosis and diagnosis is based on predefined baselines. Diagnosis can be explained as real-time measurement of stress joint's utilization. The Figure 39 shows the display of real-time measurement utilization, if the value exceeds the baseline (red line indicating maximum utilization), then the crew need to take action, either by disconnecting or changing vessel position or top-tension.

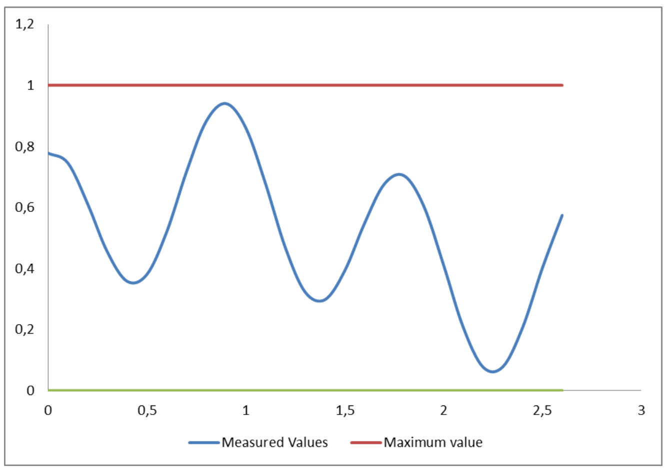


Figure 39 Example of the utilization of the equipment

The Figure 40 shows the fatigue life usage of the equipment by time. Prognosis can be explained if we can predict that fatigue usage line going to reach predesigned value. In the figure the fatigue life of current speed is given, in the same way by having forecast for current speed, it is possible to determine the more accurate time until next inspection.

Figure 40 Fatigue life tracking example (Maheshwari, Ruf, & Walters, 2008)

Advisory and display of results

Main purpose of the advisory module is to give guideline for the operator. Those guidelines are:

- Diagnosis state of the equipment (stress joint, lower stack, sensor's state etc.).
- Prognosis state of the equipment for the near future (forecasting)
- Advisory actions for the operations
  - Optimal vessel position
  - Optimal top tension
  - Inspection time

Information presented in the module needs to be clear, understandable and simple to catch. More details regarding advisory module is described in chapter 3.2, an figure 30 can be clear example for display of advisory module.

4.3. Analysis

This section will give brief overview for the cost benefit of the riser monitoring system. Most of the numbers used for the engineering and financial judgment is fictional and mainly based on my colleagues' opinion.

Average intervention time on offshore is take two weeks in NCS. The fatigue life of the stress joint is 100 days, so it should be inspected 10 times during this period; therefore it will require at least one inspection during operation. In order to inspect stress joint, all riser joints need to be taken to board, and send back after inspection. The inspection might take day of the operation. If the operating company can ensure that loads on the stress joint at least less for 10% than in normal case, then fatigue life of the stress joint can be prolonged at least for 52%. So a new inspection time will be in 15 operational days and operation can be held without any interruptions (Statoil, 2013).

It is one of the advantages of the riser monitoring system implementation, there is also other ways to save an operational time and ensure integrity of the system which also leads to high cost saving. Only Statoil in NCS has around 500 subsea wells, if each well requires intervention every 3-5 years, the company has to have at least 100 intervention operations per year. With rig rent around 6 million NOK per day and by saving one day of operation from each intervention, Statoil can save around 600 million NOK per year. Certainly, implementation of the riser monitoring system is also can be costly, especially in the initial stage, but author believes it will cover the expenses in a short period.

5. Discussion and Recommendations

Full and detailed analysis of the all riser monitoring system was not presented in the paper due to time limitation and resource constrains. The paper presents general overview for riser management system with emphasis on riser monitoring system implementation. The riser monitoring system is not a new technology, but not many companies are practicing it and there was not much research about the financial benefits of implementation. The case study presented in the paper shows how riser monitoring system applied for single riser can allow monitoring also neighboring riser joints. Also rough cost analysis shows how implementation can benefit operator.

Condition monitoring techniques are highly developed in many industries, though subsea intervention business is not widely practicing it. The author believes that there is gap on standards and codes regarding implementation of riser monitoring system for intervention operation. Global riser analysis is based purely on computational approach. Not many researches were conducted about GRA result's accuracy. It is advised to use riser monitoring system which displays both actual monitoring and GRA guidance.

It is recommended to use integrated riser management system described in the paper, which encompass all stages in WAS equipment's life cycle, and use ECM for storing and shearing information. The author believes that integrated riser management not only will benefit during the operation but also for initial design and for riser maintenance planning as well.

Life cycle cost of the system was not analyzed in the paper. For further study it is recommended to do life cycle cost analysis for the system. Detailed analysis for the measurement accuracy for different monitoring techniques needs to be done. The analysis should be verified with professional FEA software, and has to be tested at workshops.

In summary the riser management and riser monitoring systems' processes are given in general form and can be easily adopted for other fields. For instance, the processes can be implemented for subsea production or subsea processing field.

6. Conclusion

The main objective of this thesis is to show implementaion of the riser monitoring in the integrated riser management system. Operations guided purely on global riser analysis, which is based on conservative standards, limits many interventions either by smaller window or higher operational uncertainties. Unfortunatly, it is the way how most of the operator companies act. Monitroing of actual state of the equipment during operation allows to reduce uncertainty. Although, condition monitoring system is commonly used in many industries and presented in many international standards, there is not a direct guideline for implementation of the riser monitoring system in workover and drilling operations. Most of the subsea equipment highly critical only because of maintenance and inspection difficulties. Playing with critical equipment without surveillance limits operational cababilities and lead to use the equipment in inefficient way.

General processes in riser management system is presented in the paper. Firstly, process of generating operational guideline by GRA is shown. Afterwards, riser monitoring techniques from different companies is discussed and riser management and monitoring system implementation methodology is suggested. The methodology is based on different ISO standards. The methodology aims for building a system which can benefit operating companies by:

- Advising optimum vessel position.
- Advising optimum hook load and tensioner.
- Advising for inspection.
- Presenting loads on the joints.
- Showing utilization of each component etc.

Author believes implementation of the riser monitoring system can benefit by surveying permanent subsea equipment like x-mas tree and wellhead during operation, having bigger operational window and better inspection planning. In order to deal with high capital investment author suggests to start implementing riser monitoring step by step, but with future expansion capabilities. For instance, at the beginnig only for load monitoring, later with operational advice package and so on.

Finally condition monitoring technoquies are developing every year, therefore FMC should always assess existing monitoring techniques with latest monitoring techniques in the market, to stay up to data and replace out date systems.

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Appendix A

Description of crack growth model

The incremental crack growth can be described by the following way (BS7910, 2005):

$$\frac{da}{dN} = C \times (\Delta K)^{k_{cg}}$$

Whereas a is the crack depth, C and k_{cg} are linear material growth constants which depends on applied condition (e.g. corrosion) and material of the riser. ΔK is stress intensity factor and can be calculated by the following equation

$$\Delta K = S \times Y \times \sqrt{\pi \times a}$$

Whereas S is nominal stress range, Y is the correction factor for the stress can be written in terms of geometry factor f and notch field factor m_k.

$$Y = f \times m_k$$

Finally notch field factor can be written in terms of weight function of m(x) and stress in plane of the crack field $\sigma_N(x)$.

$$m_k = \frac{\int_0^a \sigma_N(x) \cdot m(x) \cdot dx}{\sigma \cdot f \cdot \sqrt{\pi a}}$$

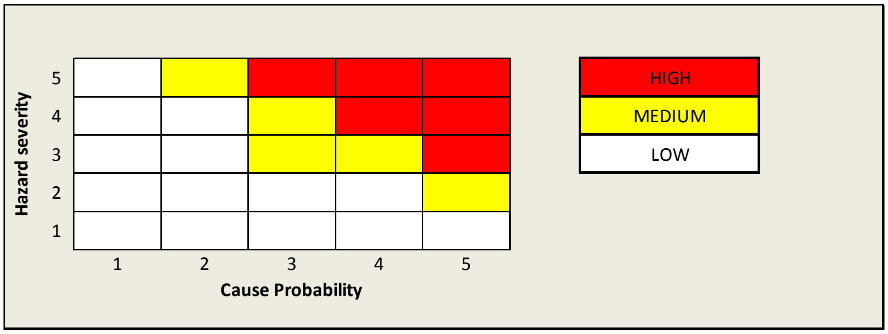
The design cycle number can be calculated by integrating Paris's equation. Whereas a_0 and a_f represent initial and final crack depths respectively.

$$N_p = \int_{a_0}^{a_f} \frac{da}{C \times (\Delta K)^{k_{cg}}}$$

In case of lack of information about initial crack depth the value 0,15 mm can be used for the calculation. The crack growth in both directions of depth and width need to be taken into account during analysis. The ration of crack depth to length need to be taken as not less than 1:5 and final crack depth should be not more than one quarter of riser's thickness or need to be found from failure assessment diagram (API-RP579, 2000).

Appendix B

Risk Martix is given in next form:



Hazard Probability (P)						
Guide words	Ranking	Industry Accounts for the (anticipated) frequency of hazard consequences based on industry experience.	Project Specific Accounts for the (anticipated) frequency of hazard consequences based on project experience.	Quantitative Quantitative probability.	Ranking	Guidewords
Frequent	5	Occurrence during operation occurs continually/frequently within the industry.	New design or application in industry without history of success.	Greater or equal to 1/10.	5	Very High
Reasonably Probable	4	Occurrence in the industry happens on a regular occurrence.	New design or application in this project, success within industry with similar operations.	Between 1/10 and 1/100.	4	High
Occasional	3	Occurrence during operation has occasionally (several times) happened within the industry.	Modified design or application in this project, success within the industry with similar operations.	Between 1/100 and 1/1,000.	3	Medium
Unlikely but Possible	2	Occurrence during operation has occurred at least once in the industry.	Modified design or application in this project, success on a similar projects in the past.	Between 1/1,000 and 1/10,000.	2	Low
Improbable	1	Occurrence during operation virtually impossible / has not been heard of in the industry.	Unmodified design/ operation used on this project successfully in the past	Less than 1/10,000.	1	Very Low
Note: Hazard probability categories are subjective and open for modification for project application purposes.						

Hazard Severity (S)						
Guidewords	Ranking	Environmental Contamination	Personnel Injury (Safety)	Equipment Damage	Ranking	Guidewords
		Accounts for the degree of possible damage to the environment if the hazard occurs.	Accounts for the degree of possible injury suffered by personnel if the hazard occurs.	Accounts for the degree of damage to equipment and for the effort to restore the equipment function to continue the operation if the hazard occurs.		
Catastrophic	5	Serious damage to the environment within the hazardous zone, where extensive intervention will be required to partially restore the environment to its previous condition, but where significant areas will remain permanently damaged or significantly damaged.	Serious injury to multiple personnel located in and around the hazard zone resulting in permanent total disability or death.	Catastrophic system loss halting the schedule until equipment replacement/repair is achieved. Significant cost incurred.	5	Very High
Critical	4	Moderate damage to the environment within the hazardous zone, where intervention will be required to 'repair' much of the damage, but where the environment cannot be restored fully to its previous condition.	Serious injury to personnel located in the hazard zone resulting in permanent total disability or death.	Serious system/equipment damage requiring special tools or repair equipment affecting schedule (several days) and incurring significant cost.	4	High
Moderate	3	Moderate, non-permanent damage to the environment within the hazardous zone, where intervention will be required to 'repair' the damage and restore the environment fully to its previous condition.	Serious injury to personnel located in the hazard zone resulting in hospitalization and/or permanent partial disability.	Moderate damage to the system/equipment requiring special tools or repair equipment affecting schedule (days) and incurring significant cost.	3	Medium
Marginal	2	Minor/insignificant damage to the environment within the hazardous zone, where damage will 'repair' naturally without intervention.	Moderate injury/occupational illness to personnel in the hazard zone resulting in lost work days.	Minor damage to the system/equipment requiring rework affecting schedule (hours) and incurring minor cost.	2	Low
Negligible	1	Insignificant damage to the environment within the hazardous zone.	Minor injury and/or occupational illness to personnel located in the hazard zone resulting in no lost work days.	Negligible/insignificant equipment damage repairable with equipment on hand resulting in no schedule delay or additional incurred cost.	1	Very Low

Note: The hazardous zone represents an area of the physical environment surrounding systems, equipment, or processes potentially suffering energetic failure, or potentially releasing hazardous material, or adversely impacting the environment in some other way.

Hazard Detection (D)

Guidewords	Ranking	Detection	Maintainability and Substituatability	Delay time	Guidewords	
		Accounts for the (anticipated) ability to detect a hazard cause prior to the hazard occurrence.	Accounts for the degree of functional loss of equipment and for the effort to restore the equipment function if failure occurs during installation or operation	Accounts for the (anticipated) delay of occurrence of the actual hazard/failure following the cause. Delay time allows for detection/corrective action.		
Absolute Uncertainty	5	There is no means to detect the hazard cause prior to hazard occurrence.	Greater than 20 days	Hazard/failure follows instantly/ immediately without warning after the cause allowign no time for detection and/or corrective action.	Immediate	Very High
Remote	4	Hazard cause is difficult to observe and has a remote chance of being detected prior to hazard occurrence.	5-20 days down	Hazard/failure follows suddenly after the cause, but wit hsome warning, allowing minimal time for detection and/or corrective action.	Sudden	High
Moderate	3	Hazard cause is observable and has a moderate chance of being detected prior to hazard occurrence.	from 2 to 5 days down	Hazard/failure follows the cause with a moderate amount of time for detection/corrective action.	Moderate	Medium
Certainty	2	Hazard cause is conspicuous and has almost certain chance of being detected prior to hazard occurrence.	0,5 to 2 days down	Hazard/failure follows gradually after the cause with sufficient time and/or opportunity for detection or correction.	Gradual	Low
Absolute Certainty	1	Hazard cause is indubitably obvious and is absolutely detectable prior to hazard occurrence.	less than 0,5 days	Hazard/failure follows gradually after the cause with sufficient time and/or opportunity for detection or correction without any impedemtn of operaitons.	Very Gradual	Very Low

Note: Hazard detection categories are subjective and open for modification for project application.

Item	Component Description	Function	Phase	Failure Mode	Line #	Failure Cause	Failure Effect		Engineering safeguard/ prevention/detection	Comments	RISK EVALUATION			Recommendation
							local	end			severity	Probability	Risk Category	
1	Tension Joint	Speciality joint that connects the tensioner assembly which provides the correct amount of over-pull on the riser bodies from experiencing compressive loading. Usees three pitch wave profile, single body forging. Uses clamp assembly to support load ring, slip lock into load ring.	Shipping , handling and transportation	General wave form thread damage (deformation due to contact).	1	Dropped/contact with foreign objects.	Inability to attach load ring.	Schedule delay (repair or replacement may be necessary).	Exposed threads to be wrapped with rubber sheet during shipping/handling and ship/handle in dedicated	Safeguard in place.	2	1	2	
			Shipping , handling and transportation	General damage to 11-3/4" coupling thread prevents proper seal.	2	Dropped/contact with foreign objects.	Inability to seal.	Possible drilling fluid leak to environment (if not detected/corrected prior to drilling operations).	1. Pressure testing is required after installation prior to service. 2. Tension joint is spared to reduce downtime.		3	3	9	
			Shipping , handling and transportation	General damage to 11-3/4" pin thread on tension joint prevents proper seal.	3	Dropped/contact with foreign objects.	Inability to seal.	Possible drilling fluid leak to environment (if not detected/corrected prior to drilling operations).	1. Pressure testing is required after installation prior to service. 2. Tension joint is spared to reduce downtime.		3	3	9	
			Installation.	Lost hardware (slip, retainer pin, etc can drop into ocean).	4	Human error during installation	Schedule delay (repair or replacement may be necessary).		Load ring is spared to reduce down time.		3	3	9	
			Installation.	General load ring damage.	5	Contact with foreign objects.	Damage to equipment - dropped riser.	Catastrophic failure: complete system loss.			5	2	10	Investigate spare load ring / sparing philosophy.
			Installation.	Debris strikes threads causing damage/ deformation.	6	Mill scale/debris in system.	Thread damage.	Schedule delay (repair or replacement may be necessary).	Installation procedures calls for thread cleaning and inspection.	Procedural safeguard in place.	2	4	8	Update procedure to include visual inspection of bore prior to upending, prior to placing caps on.
			Installation.	Debris strikes threads causing damage/ deformation.	7	Foreign object debris.	Thread damage.	Schedule delay (repair or replacement may be necessary).	Installation procedures calls for thread cleaning and inspection.	Procedural safeguard in place.	2	4	8	Update procedure to include visual inspection of bore prior to upending, prior to running.
			In Service.	Structural failure of Load Ring.	8	Excessive cyclical loading.	Loss of Riser.	Catastrophic failure: complete system loss.		Safeguard in place.	5	2	10	Investigate regular MPI and greasing shackles.
			In Service.	Structural failure of Load Ring.	9	Accelerated fatigue due to wear.	Loss of Riser.	Catastrophic failure: complete system loss.		Safeguard in place.	5	2	10	Investigate regular MPI and greasing shackles.
			In Service.	Load ring failure to retain riser.	10	Overloading.	Loss of Riser.	Catastrophic failure: complete system loss.	Designed to API requirements. Load case 1(max operating): 440 kips per arm Load Case 2 (survival): 600 kips on two arms. Load ring to be load tested with pre & post MPI.	Safeguard in place.	5	1	5	

2	Standard Joint	Outer conduit for drilling operations to run from the rig to the TSJ/TBC. Conduit to facilitate the drilling operation connecting the top side equipment to the WH.	Shipping, handling, and transportation.	General damage to equipment.	11	Contact with foreign objects during transportation.	Schedule delay (repair or replacement may be necessary).		1) Protector caps to be provided for all sealing surfaces.	Safeguards in place.	3	2	6	Investigate spares.
			Shipping, handling, and transportation.	Personnel injury due to dropped load.	12	Inability to manhandle protective caps.	Injury to personnel.	Potential for lost work day incident.			2	3	6	Investigate the weight and ability to manhandle caps.
			Shipping, handling, and transportation.	General damage to threads.	13	Difficulty in unscrewing caps mandates undesired operations.	Schedule delay (repair or replacement may be necessary).				3	3	9	Investigate the difficulty in unscrewing of caps (want to mitigate the use of sledge hammers to loosen caps).
			Installation.	General damage to equipment.	14	Connection contact with rig/deck during installation.	Schedule delay (repair or replacement may be necessary).		1) Permanent guide funnels shall be provided for the deck opening (both top and bottom).	Safeguards in place.	3	1	3	Investigate spares.
			In Service.	Structural failure.	15	Hydrogen embrittlement.	Loose riser.	Schedule delay (repair or replacement may be necessary).	1) Proper material selection. 2) Incorporate lessons learned from BP failures. 3) Proper preload in studs via stud tensioners and not torque tools. 4) Regular inspection.	Safeguards in place.	4	1	4	
			In Service.	Structural failure.	16	Improper buck-up torque.	Loose riser.	Schedule delay (repair or replacement may be necessary).		FEA to confirm proper preload.	4	1	4	Perform make/break tests to verify tooling reliability & repeatability.
			In Service.	Structural failure of Load Ring.	17	Excessive cyclical loading.	Loss of Riser.	Catastrophic failure: complete system loss.		Safeguard in place.	5	2	10	Investigate regular MPI and greasing shackles.
			In Service.	Structural failure of Load Ring.	18	Accelerated fatigue due to wear.	Loss of Riser.	Catastrophic failure: complete system loss.		Safeguard in place.	5	2	10	Investigate regular MPI and greasing shackles.
			In Service.	Load ring failure to retain riser.	19	Overloading.	Loss of Riser.	Catastrophic failure: complete system loss.	Designed to API requirements. Load case 1(max operating): 440 kips per arm Load Case 2 (survival): 600 kips on two arms. Load ring to be load tested with pre & post MPI.	Safeguard in place.	5	1	5	

3	Stress Joint	Stress joint accommodates the large stress and deflections. Flanged up to tieback body. Bolts are pretensioned. ROV can replace stabs after pulled prior to running. One stab locks, the other for testing/secondary unlock (testing will not be plumbed). Flat to flat lock.	Installation.	Pressure leak	20	Damaged sealing surface	1) Use spare TSJ. 2) Break apart the existing TSJ/TBC assembly and re-mate with spare stress joint.	Schedule delay (repair or replacement may be necessary).	1) Protector caps to be provided for all sealing surfaces. 2) Clear procedures on handling cleaning and inspection to be provided.	This will be very time consuming and inherently risky to make this connection on the rig.	4	2	8	Suggest sending equipment to the beach to perform this operation. MUST ensure proper pre-load on studs of the TSJ/TBC assembly.
			Installation.	General gasket damage.	21	SJ contact to top of well head during installation.	Schedule delay (repair or replacement may be necessary).				3	3	9	1) Tag lines recommended. 2) Installation limits should be based on sea state.
			Installation.	Connector unlocked.	22	Pressure is applied to the incorrect port.	Drilling fluid release to the environment.	1) Environmental contamination. 2) Loss of drilling fluid.	1) Visual check required on both the release rods and connector location. 2) The ball valve shall be closed after setting hump.	Safeguard in place.	5	1	5	
			Installation.	Low locking pressure.	23	Outer cylinder is incorrectly positioned during installation.	Capacity reduction.	Schedule delay (repair or replacement may be necessary).	1) Outer cylinder has conspicuous tell-tale marker. 2) Procedures call for visual verification. 3) Procedures call for set screw check.	Safeguard in place.	3	1	3	
			Installation.	High locking pressure.	24	Outer cylinder is incorrectly position during installation.	Inability to lock connector.	Schedule delay (repair or replacement may be necessary).	1) Outer cylinder has conspicuous tell-tale marker. 2) Procedures call for visual verification. 3) Procedures call for set screw check.	Safeguard in place.	3	1	3	
			Installation.	Debris strikes threads causing damage/ deformation.	25	Foreign object debris.	Thread damage.	Schedule delay (repair or replacement may be necessary).	Installation procedures calls for thread cleaning and inspection.	Procedural safeguard in place.	2	4	8	Update procedure to include visual inspection of bore prior to upending, prior to running.
			In Service.	Pressure leak.	26	Damaged Gasket.	Drilling fluid release to the environment.	1) Environmental contamination. 2) Loss of drilling fluid.			3	3	9	1) Identify the number of make/breaks prior to seal change-out. 2) Write ICP that clearly identifies how this is to be performed.
			In Service.	Structural Failure.	27	Failure propagation based on material defect.	Loss of Riser.	Complete system loss.	1) Impose stringent manufacturing specifications 2) 3rd party witness during manufacturing process.	Safeguard in place.	5	1	5	
			In Service.	Structural failure.	28	Excessive cyclical loading.	Loss of Riser.	Catastrophic failure: complete system loss.		Safeguard in place.	5	3	15	Investigate regular MPI and greasing shackles.
			In Service.	Structural failure.	29	Accelerated fatigue due to wear.	Loss of Riser.	Catastrophic failure: complete system loss.		Safeguard in place.	5	3	15	Investigate regular MPI and greasing shackles.
			In Service.	Structural Failure.	30	Overloading.	Loss of Riser.	Complete system loss.		Ensure proper design with sufficient SF.	5	2	10	Ensure proper design with sufficient SF.