Risers and Mooring Lines Integrity Management based on Real-Time Integrity Monitoring.

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Abstract

In the past few years there have been a number of deepwater flexible risers and mooring lines which have failed during operation. These failures present significant environmental, safety, and physical costs, and these can be avoided by the use of monitoring combined with a carefully managed integrity management system.

The majority of the known cases of critical damage to flexible risers concern the armour wires at the top section of the riser, whereas recent mooring line failures have occurred at both their top and bottom sections. Flexible riser failure is usually gradual, due to successive armour wire breakage and typically occurs at the section located inside the I-tubes, where diver and ROV visual inspection are not viable. Conversely mooring failures are often sudden, but due to incorrectly managed, defective or non-existing monitoring systems it is not uncommon for the failure to go undetected for several months. This leaves the vessel, riser systems, and any other connected structures vulnerable to overload, and consequently increased risk to personnel, the environment and asset production, without the Operator being aware and able to take corrective or mitigation measures.

Often Operators only appreciate the need for monitoring and integrity management after an expensive failure or prolonged shut-down, or in the worst case a fatal accident. The objective of this paper is to inform Operators of innovative, retrofitable, on-line monitoring systems which have been developed to monitor the integrity of mooring lines and flexible risers. They can also be used to provide key data for a higher level of integrity assurance of these critical offshore components; and hence avoid failures.

Whilst the main objective of an on-line monitoring system is to identify anomalies during operation, invaluable understanding of the system performance as a whole can be obtained if an integrity management approach is adopted. Historical records of in-field performance of a single or a number of structures being monitored, together with correlation with other associated data, such as platform position and environmental data, provides a robust tool to validate mooring line and flexible riser performance against design, and also to facilitate the improvement of future designs.

Introduction

Particularly in deep water and hostile environments, where loading is high and complex and often design methods are pushed to the limit of current industry capability and experience, mooring lines and flexible riser systems have gradually received an increased focus, more than ever in the light of recent storms which have caused operators and regulators to question and update codes of practice. In recent years, there have been a number of discussions in industry, papers written, JIPs commissioned, and research undertaken about the main operational problems and actual failures mechanisms of these systems. Despite the criticality of these components, integrated and coordinated integrity management approach is often found to comprise of only irregular diver inspections, with very little monitoring equipment prescribed, if any at all. In other cases, even when detailed and regular inspection programmes are conducted or Class is adopted, for the majority of the installed systems there is a lack on actual real-time and historical information of mooring and riser structural performance. Often where monitoring systems have been prescribed, there has not been sufficient thought put into what data was required to be collected, who should be responsible for the data, and what needed to be done to the data to provide valuable information on component performance. As such, monitoring systems did not seem to be delivering warning of integrity breaches as may have been expected for such safety critical items. In addition, as a result there has been a lack of suitable tools to identify anomalies during operation and better understand the system as a whole.

Mooring systems for harsh environments, and particularly for deep and ultra-deep water, do not have significant design contingency to withstand survival conditions, as is illustrated by the average FPSO mooring failure recurrence in the UK of 5.4years (6) where water depths are not as extreme as in the West of Africa. Despite the failure frequency, a similar scenario is also experienced by flexible risers, whose technology is being pushed close to design limits. Whilst a mooring failure is not desired, it can usually be accommodated in an extreme situation if no further extreme loading condition occurs simultaneously. However, a catastrophic riser failure, especially for a production and pressurized riser, would not only dominate the headlines around the globe - affecting Operator reputation - but would also immediately affect production. With the volatile oil and gas prices of recent years, this could seriously affect the ongoing viability of an installation.

It is not uncommon in parts of the world to hear from Operators that mooring failures have gone undetected for up to 6 months, until the next prescribed subsea inspection. Besides the fact that most of the units (67% in the North Sea) do not have mooring line spares available, the overall business interruption impact of a single mooring failure can add up to more than $10M for a 250,000 bpd FPSO offshore WoA, when anchor handling (AHV) and ROV support vessels are considered (3). If a shutdown is required the figure above can be multiplied by many times.

Monitoring within an Integrity Management Scheme

Responsible operators have been recognizing the importance of implementing risk-based integrity management programmes to mitigate the inherent uncertainty in the life of field risk profile of these critical systems. Such programmes are based on a systematic assessment of the potential failure modes and development of risk mitigation plans including specification of inspection and monitoring, and plans to quantify actual performance and identify anomalies.

Mooring and flexible riser systems degrade and fail for a range of reasons and ideally during the design phase monitoring and mitigation should be defined in conjunction with inspection following risk assessment of the components (see Figure 1 below). For underwater components which are not easily accessed or viewed, it is normally the case that mitigation and monitoring play a key role in integrity assurance due to the limited information provided by inspection while monitoring can provide a cost effective means of providing data which can be used to assure ongoing integrity.

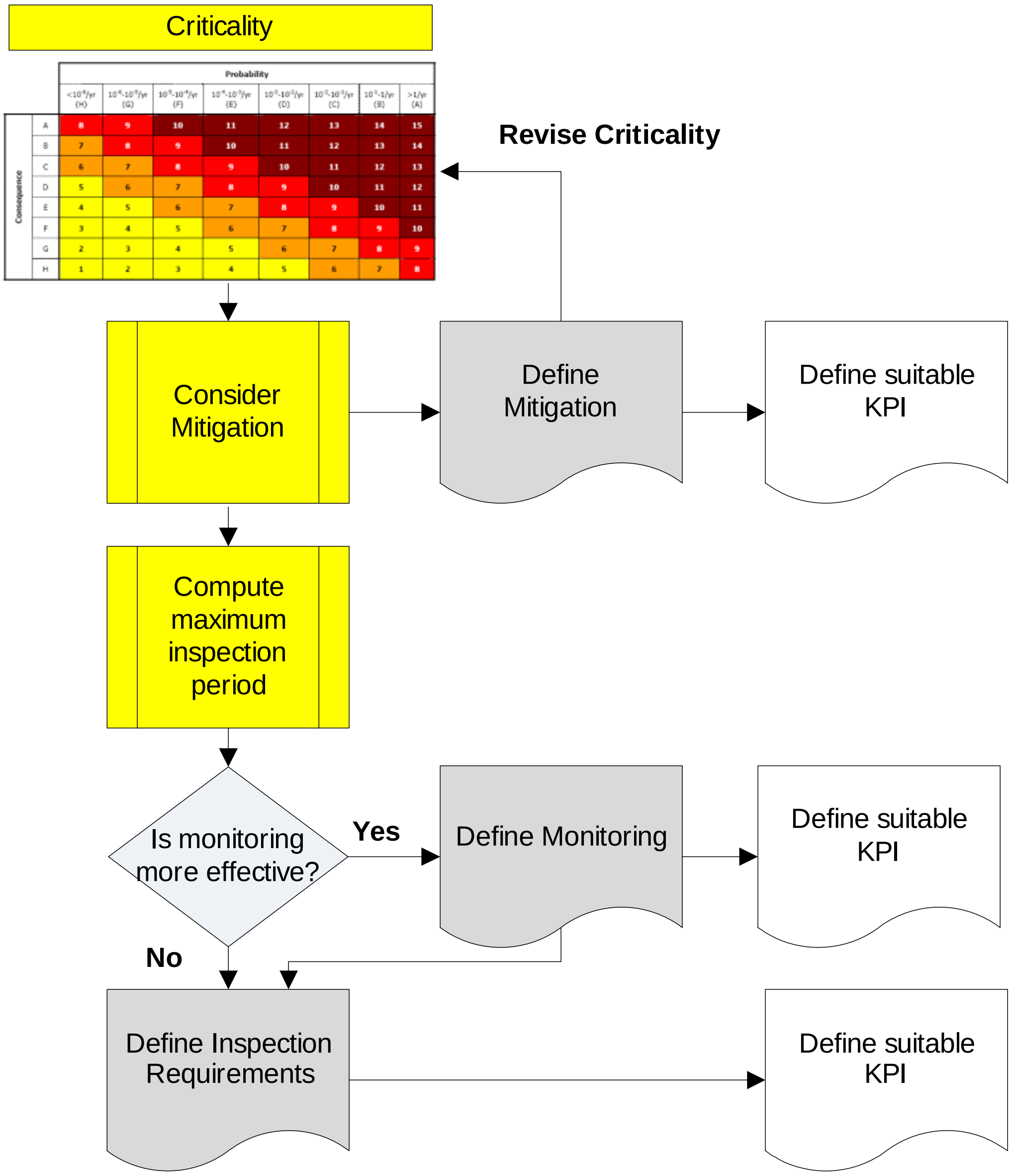

Figure 1 - Integrity Assessment Process

Improvements in long term integrity are needed, together with better understanding of overall system behaviour and failure mechanisms. Therefore, key performance indicators (KPI) are an important aspect of effective integrity assurance for compliant underwater components such as moorings and risers. Often systems go into production without sufficient consideration having been given to Integrity Assurance; however, while the options for mitigation and monitoring are more restrictive at this stage, and may be more expensive to implement, retrofit solutions are available, as shown in Figure 2.

Figure 2 – Retrofit Mooring Line Monitoring System

During operations, on-line monitoring system, together with inspection, support assurance activities on the integrity of flexible risers and mooring lines which can be summarized and grouped as follows:

- Past – validate performance against design assumptions and expected limits;
- Present – provide operational assistance, assure system is behaving within designated limits and identify anomalies and deteriorative process before damage build up and consequent failures;
- Future – provide historical record to help expand understanding of the systems complexity and develop enhanced future systems to mitigate operational issues or improve performance results and operational confidence.

Typical Current System Methods and Limitations

Inspection on its own provides only limited information on the integrity of mooring and riser components. Inspection methods traditionally used for deepwater mooring system usually emanate from two different areas (5): class society requirements developed for ships plying trade routes, and fixed installation practices. As a consequence, although for mobile offshore drilling units (MODU) mooring recovery is a periodic requirement and traditional dry inspections are feasible, for permanent moored platforms recovery and reinstallation have an associated risk, if possible, depending on equipment available. In many units even the line length can not be adjusted.

While dry dock inspection allows access to some areas which are not reachable underwater, it is often not desirable to dry dock an FPS and in-water inspections are more cost- and time-effective allowing easy identification of chain sections located close to the fairlead and the touch down zone, usually subject to higher damage and deterioration.

Figure 3 – Left: Excessive Marine on a Long Term Deployed Chain (3).
Figure 4 – Right: Wear and Corrosion on a Chain Link from the Seabed Touch Down Zone (3).

In water inspections of mooring components require that varying levels of marine growth are removed such that divers or ROVs can have visual access, conduct dimensional measurement and assess structural condition. However, there are other methods for removing marine growth, each with advantages and limitations. Furthermore, besides the time and cost required for cleaning of marine growth and scaling by high pressure water, it may well accelerate corrosion by exposing fresh steel to salt water.

In relation to flexible risers, for the majority of the reported cases, damage is located in the top section of the riser, close to the bend stiffener (2). These include external sheath damage, corrosion and/or fatigue induced damage to the tensile armours, and torsional instability associated to tensile armour rupture.

Figure 5 – Left: External Sheath Damage Caused by Bend Stiffener Contact at the I-Tube (2).
Figure 6 – Right: Tensile Armour Wires Rupture on a Flexible Riser (2).

Contact between the riser and platform hull or repeated clashing against another riser are common causes, especially on semi-submersible units, due to the large drift of the platform. In the I-tubes it is common to find damage to the riser in the form of external sheath abrasion and breaching caused by interference with the bend stiffener internal insert. As large diameter flexible risers get close to the threshold of flexible construction technology, the armour wires become more sensitive to fatigue, especially in high stress concentration regions such as the interior of end fittings. Therefore, there is limited information which can be assessed by diver and even less by ROV inspections.

For flexible risers which have a top I-Tube, divers are often required to lower the bend stiffener to have additional visual access, but still can not go inside the I-tube. Even at sections not surrounded by I-tubes, the flexible riser outer sheath limits the visual evaluation of the armour wire condition itself. Divers/ ROV pilots usually look for protrusions, deformations and damage on the outer sheath, which may indicate that armour wires are broken inside or water has been able to ingress inside the protective external layer. The exact extent of the damage and actual operational risk to keeping production relies mainly on diver and operational personnel experience.

On the one hand, despite its limitations, inspection methods help evaluate mooring and riser component condition; but on the other hand they usually do not provide any performance indication. Such information is often supplied either by monitoring systems, or by periodic tension measurements based on inclination measurement by divers or tension meters. However, from the majority of the North Sea based FPSOs, where good indicative statistics are available, 50% of the units can not monitor line tensions in real time (3).

2H Offshore’s own experience from Operators feedback is that the majority of the vessels are designed with built-in monitoring system; however, during initial operating years they become inoperable, require constant re-calibration or provide unreliable readings. It is believed that this may be due to the integrity assessment (as described above) not being undertaken during design and as a result the need for the monitoring data was not fully established and consequently responsibility was not allocated to ensure the data is fully assessed and integrity assurance information derived.

Tension measurements based on the base of pull-in winches are typically very poor, with deviations from direct catenary calculations of more than 100% in a number of cases. As a consequence of the inherit friction, which is difficult to quantify, even for properly calibrated systems, a pull-out / pull-in test for a specified mooring length can have tension varying by more than 20%.

For both riser and mooring lines, a typical basic method for assessing the system configuration is to measure the inclination with the vertical. This method is used following installation and after months or years of operation. However, depending on the method used there are some intrinsic sources of uncertainties, which are difficult to quantify, and limitations of the indications provided. Measurements are usually performed by a diver with a manual inclinometer, and despite being measured in a sequence, the few hours difference between the measurements of each mooring line (up to 18 for some FPSOs) may affect their correlation due to environmental loading, vessel heading and offset variations during the time. In addition, despite a relative common calculation, there have been cases when it is reported that there are difficulties requiring a few weeks to get the tension inferred from the inclination measured based on mooring properties and basic catenary calculations, due to non-centralized data management.

Regardless of its limitations to assess operational fitness of the whole system, specially to define causes and provide real-time alerts, visual inspection methods are invaluable in assessing mooring and riser components, in order to give insights for degradation process, particularly such as corrosion, indentation, wear, friction bending, loose studs, and others.

On-Line Monitoring Systems

Based on the historical background and the integrity management requirements that can not be fulfilled by inspection campaigns alone, 2H Offshore has developed innovative on-line monitoring systems. Despite the different nature and different applications of the systems, flexASSURE™ (flexible risers) and moorASSURE™ (mooring lines) have similar basic components and can be used in a similar manner within a risk based integrity management programme.

Both systems are retrofitable, and therefore can be installed during riser or mooring line installation or after the structure is already in place. Both systems are non-intrusive and do not affect the behaviour of the components which they are put in place to monitor. These systems have been qualified in laboratory tests and are based on subcomponents, INTEGRIpod™ sensors, which have been used in more than 200 campaigns. The respective ASSURE systems have already been installed offshore in both permanent and temporary campaigns. In addition to successful flexible monitoring campaigns within a laboratory environment, the flexASSURE system has been installed on a flexible riser in Campos Basis, offshore Brazil (1). The moorASSURE™ system is also operating successfully for projects such as the SBM/Shell on the Espírito Santo FPSO, in Campos Basin block BC-10, offshore Brazil where it has operated successfully since May 2009.

One basic difference between the two systems, is that the FlexAssure system, due to the large amount of data that needs to be measured and transferred to the topsides, requires a hardwired system while the MoorAssure system may rely on a hydro-acoustic transmission between the inclination sensors connected onto the mooring lines and the receptor-modems located at the vessel hull.

moorASSURE™

The moorASSURE™ mooring line monitoring system is used to confirm the integrity and the performance of mooring systems by monitoring the mean angle of mooring lines and infer the mean tension from it. On each mooring line, an INTEGRIpod™ inclinometer is attached to measure its mean angle. Using hydro-acoustic data link, the measured angle is periodically transmitted to vessel mounted acoustic receivers. The measured mooring line angles are collected by a topside data acquisition system. Using the measured mooring line angles and incorporating vessel GPS and vessel draft data, the mean tension of each mooring line is deduced using a mooring line mathematical model.

The INTEGRIpod™ acoustic inclinometer is placed in a holder to allow its retrieval and installation by ROV or diver. The logger holders can be attached to chain links or on the chain follower below the chain table. A number of hull-mounted acoustic receivers are connected using electrical cables to an industrial rack mounted data acquisition system located on the topside. The calculated mooring line tension is displayed and compared with preset thresholds. Where measurements exceed predefined threshold, alarms are raised by the software.

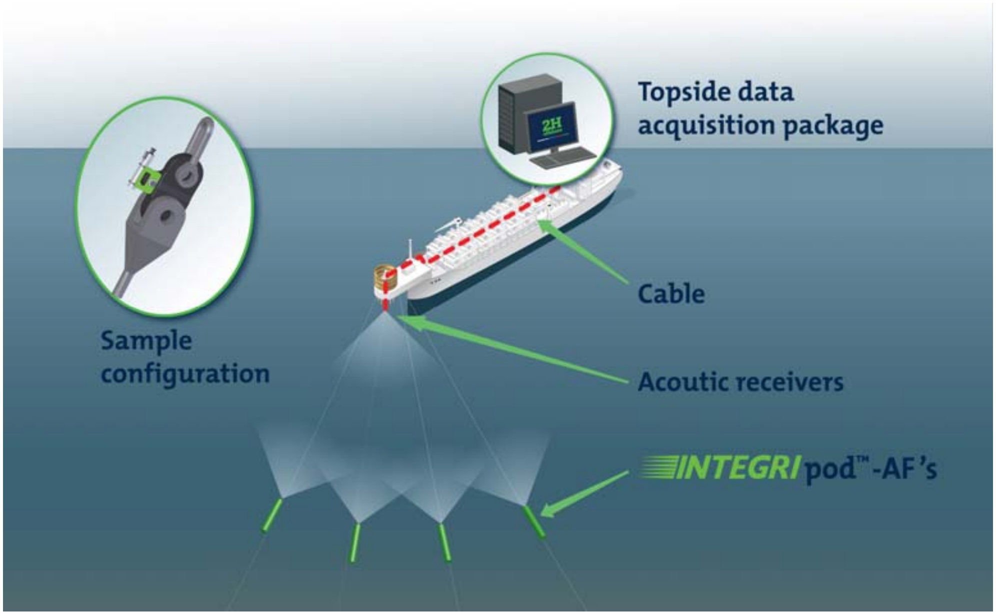

Figure 7 – moorASSURE™ Monitoring System Schematic Description

The average tension monitoring system can also be integrated with the INTEGRIcuff™, a retrofitable dynamic tension sensor. The INTEGRIcuff™ is placed inside the mooring link, transversely to the line axis, and measures the transversal strain generated by dynamic fluctuation of the chain tension. The conversion from strain into dynamic tension is performed using a correlation developed by finite element analysis (FEA).

flexASSURE™

In order to provide confidence in the flexible riser's integrity, or to alert on the build up of damage, 2H has developed the flexASSURE™ system. The flexASSURE™ uses state-of-the-art sensors to detect the following key parameters on-line, providing instant feedback at the vessel, as along with relaying the data to 2H's and Operator's offices for more detailed analysis and identification of long-term trends, such as:

- Armour wire failure detection – using a range of sensors to identify the signature response when an armour wire under tension breaks;
- Presence of gas build-up in the pull-tube – using a gas detection system in the I-tube;
- Detection of the build-up of corrosive gases in the riser annulus – using a gas detector on the riser vent valve;
- Vessel offset monitoring - via integration with vessel GPS system;

- Riser top tension - comparing vessel offsets and riser top angle, the riser top tension is recorded, and periods of excessive tension identified;
- Riser Vortex Induced Vibration (VIV) – using accelerometers and inclinometers on the riser to detect VIV signatures.

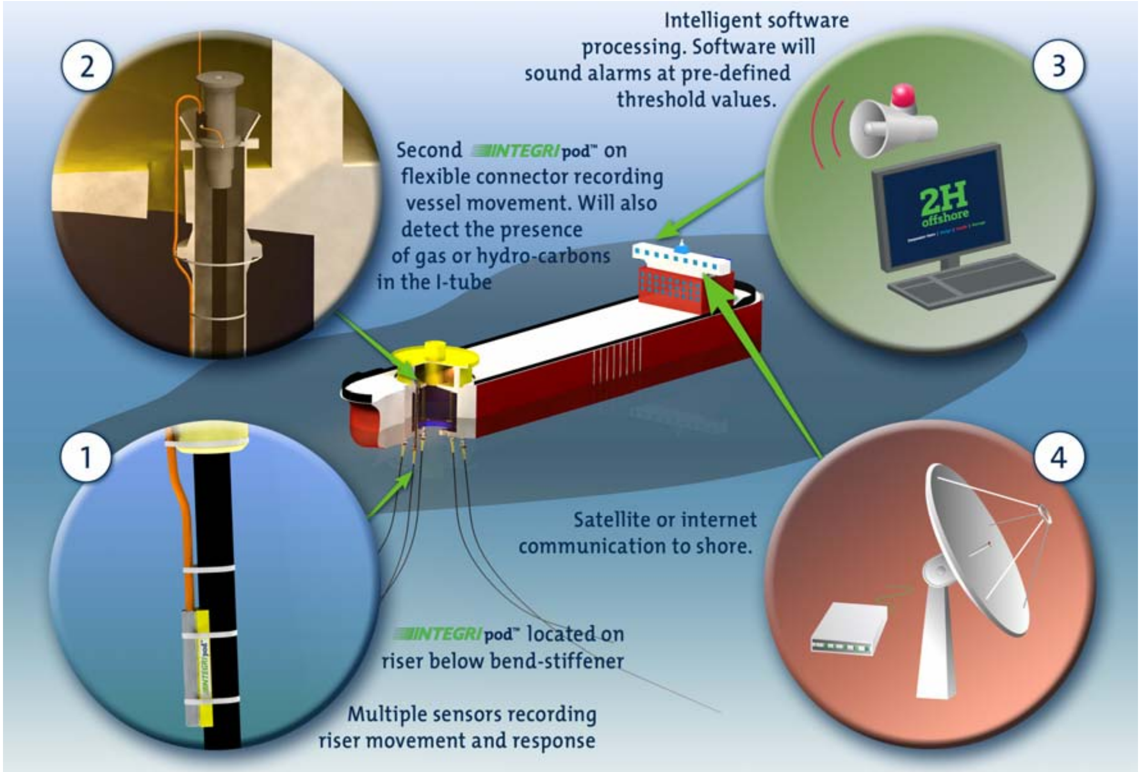

Figure 8 – flexASSURE™ Monitoring System Components Overview

The full-system integrates different assurance sub-systems to capture the riser response and failure mechanisms. A collection of monitoring devices is mounted onto the riser below the bellmouth, in a low profile housing, installed using divers. This pod records riser motion, inclination and acoustic emission. The INTEGRIpod™ is hardwired, providing power and communication to log the sensors constantly and at a sufficiently high frequency to capture armour wire failure.

A second INTEGRIpod™ is mounted on the riser end termination that is rigidly connected to the vessel structure. It contains a series of motion and acoustic sensors to record the movement and acoustic emission at the end termination. This allows vessel motions to be accurately captured at the termination point and the important difference across the I-tube and bend stiffener to be determined. Gas detectors and pressure sensors are also used to monitor presence of hydrocarbons, and pressure build-up in the annulus space, which are indicative of the outer carcass integrity.

The INTEGRIpods™ are hardwired to a standard PC fitted with a global positioning system and satellite communications system. Sophisticated but stable software combines the signals from the sensors on the bellmouth and connector INTEGRIpods™ and processes them using algorithms developed by 2H to detect anomalies, the presence of armour wire failure, VIV, excessive tension, presence of dangerous gases in the I-tube and extreme vessel offsets.

Figure 9 – flexASSURE™ Monitoring System Data Management Scheme

On-Line Monitoring Filling the Gaps of Inspection

In addition to the areas not accessible by ROV or diver inspection, there are a number of specific parameters in relation to which the described on-line monitoring systems play a key role:

- Anchor slippage / Suction Pile Displacement – this may happen suddenly due to harsh whether or gradually and only be detected from a wider evaluation, where the reduction in top angle and associated top tension can be recognized as not being a temporary consequence of the whether condition or polyester creep (if applicable).
- Polyester Creep – Expected, particularly in the early operational years, that the polyester lines have a permanent increase in length (creep). Identifying the occurrence of this phenomenon and quantifying it, such that appropriate retensioning can be carried out before the line becomes to slack is an automated function of the monitoring software, shall GPS data be available and integrated.
- Correlation of Mooring and Risers Performance – in order to increase the confidence rating of its performance, when a number of mooring lines and risers are being monitored simultaneously, it is possible to:
    a. Associate events observed from different moorings and risers and correlate with environmental loading, structure specific events (clashing, slugging, VIV), or any unexpected behaviour, making it more straight forward to disregard non-relevant events and identify potential issues.
    b. Carry out analysis of the statistical behaviour of each mooring line/ riser and the set of structures from the same and from different platforms, based on historical data.
    c. Base operational decisions on the real-time tension verified on the mooring lines and/ or risers, particularly for turret moored FPSOs, during operations that require specific vessel positioning or heading, such as pull-in/pull-out operations or during connection to an offloading vessel.
    d. For vessels equipped with dynamic positioning (DP) system, the on-line information can be used to optimize rig location, whilst for moored drilling rigs it can support disconnection decisions.

- Real-Time Operational Limits:
    a. When a mooring line has failed, due to lack of spares and the logistics for replacement, it may be necessary to carry out production in extreme conditions for a period. In such a situation, the environmental limits must be defined to support the decision to continue production. Real-time monitoring of moorings and risers can be used to assure critical limits are not exceeded and to identify unacceptable risk in situations and avoid failures before they may occur.
    b. In case of an armour wire failure on a flexible riser, the on-line system can be used to monitor changes in riser performance and also monitor the occurrences of further wire breaks. Since the riser can continue operation with a limited number of broken wires, quantifying the event is key for continued operation while providing confidence even in an extreme situation.
- Dynamic Measurements – The basic operation of the moorASSURE™ system relies on the measurement of average tension. However, there is an optional sensor package for the system, the INTEGRIcuff™, which can be used to monitor dynamic fluctuation of the link axial tension. These can be specially used to investigate and better understand failures resultant from dynamic pinching/ grinding between links. The comparison with design assumptions can also be used to predict cumulative excessive damage before a failure.
- Friction Induced Bending – on a tensioned chain, there is some inherit interlink friction which can cause friction induced bending. The higher the tension in the line, the greater the frictional forces. Therefore, even if the mooring line is operating within predefined tension limits, the long term occurrence of unexpected high tensions may be detected and through an integrity management evaluation suitable remedial actions may be prescribed. These could include the slight adjustment of the tension distribution of the mooring lines, both to reduce excessive tension and to change the most critical links, (those located on the most dynamic section, the touch down point (TDP) and just outside the chain hawse or chain follower, or bell mouth, as applicable).

Conclusions

The tools available for integrity assurance of compliant subsea components are restricted as visual inspection by ROV or diver provides only limited information on the condition of components. As a result, greater reliance is placed on condition and load monitoring along with mitigation measures. Associated with these activities key performance measures with predefined alarm levels are essential. Regular reporting of these key performance indicators ensure that personnel are aware of the value of the barriers put in place and static and dynamic load levels within components compared with design parameters.

Implementation of risk based integrity management plans for subsea systems have resulted in significant value to the operators. An effective Subsea IM programme includes risk based integrity (RBI) assessment, monitoring and inspection plans, key performance indicators to provide alert levels, and anomaly tracking and resolution. The advantages gained include reduced asset downtime, improved understanding of subsea structure performance to extreme loading conditions, clear estimation of remaining life, confirmation if an event resulted in damage to the structure (and therefore rapid confirmation of ability to resume production), improved anomaly tracking with clear management strategy on schedules, improving cost efficiency by targeting inspection on critical areas, evidence of poor material selection leading to anomalies which can be avoided/better engineered for future projects.

Looking ahead, system designers can dramatically improve the ability to perform conditional monitoring by planning for and providing in the system designs the necessary instrumentation to permit better conditional monitoring. A few additional basic subsea measurements would enable more precise fault detection and source identification than is possible with most systems today.

There are a number of direct advantages of having an on-line monitoring system for both flexible risers and mooring lines, including being able to actively support operational decisions and being able to assure operations personnel and regulatory bodies that the structures remain within safe operational limits extreme events. For mooring lines, monitoring gives confidence to operations personnel that all lines are connected which is basic information which is often not available through other means.

With the input of experienced mooring and riser personnel, predefined response procedures can be built into the monitoring software providing immediate alarms and predefined actions can be initialized both on and off shore if any performance measure is breached. This will ensure personnel safety is upheld while the environment is protected and asset availability is maintained. Events trigging response above agreed threshold limits may include any sudden change in instrumentation readings or incoherent behaviour between two opposing mooring lines (whose tension and angles are expected to be mirrored).

Data recorded on the vessel may be stored in a database for each riser, and/ or mooring line which may be made available to 2H engineers by internet link or for periodically review. This would enable regular reporting of identified anomalies, and ongoing integrity assurance. 2H would be able to identify key events, long-term trends and concerns, and issue technical integrity reports on a regular basis. 2H would then recommend remedial actions or activities to confirm integrity.

One key aspect of the Integrity Management approach is that integrity assurance activities need to be planned and not simply be reactive, by managing risk and improving safety. It should also be noted that certain limits must be viewed in conjunction with other events rather than treated as isolated indicators. Extreme design conditions, for example during a significant storm, could result in large bending and axial stresses. When combined with the resulting shut in pressure high hoop stresses may be generated and, in combination, could over stress the system if not considered simultaneously.

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Pictures

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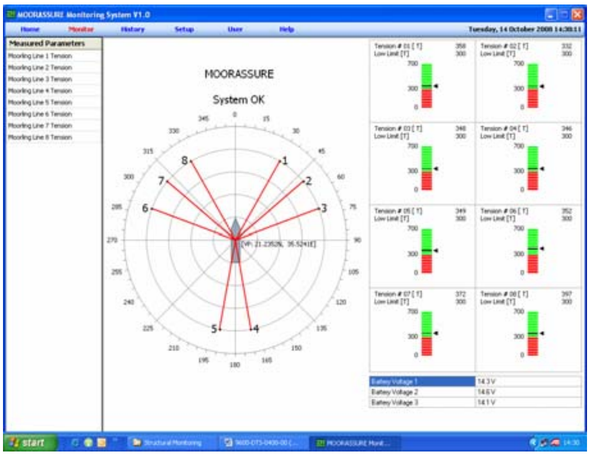

Figure 10 – Left: moorASSURE Main Software Screen.
Figure 11 – Right: Diver/ROV Replaceable INTEGRIpod Connected to Chain Follower in Shell BC-10, Espírito Santo FPSO.

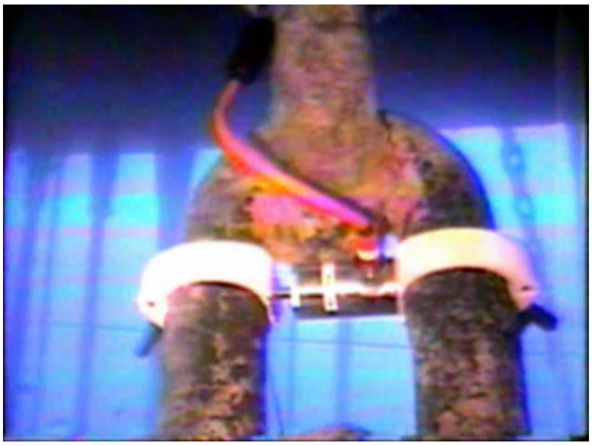

Figure 12 – Left: INTEGRIcuff – Dynamic Chain Monitoring Device, installed in P-35 FPSO, offshore Brazil.
Figure 13 – Right: INTEGRIpod with acoustic transmitter and acoustic receiver modem used.

flexASSURE™

Figure 14 – Left: flexASSURE Lab Test at COPPE, Federal University of Rio de Janeiro, Brazil.
Figure 15 – Right: Notch creation on Armour Wires During Lab Test.

Figure 16 – Left: View of flexASSURE Sensor in a Prototype Casing Installed Offshore.
Figure 17 – Right: Artistic Schematic View of Sensors Installed Subsea.