Consistent Integrity of Mooring System

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ABSTRACT

The proposed paper is going to review and assess the different ways of achieving more robust mooring system as requested by some operators/contractors. This review is not limited to design activities but also integrates impacts of procurement, transport, installation and operation phases onto the overall integrity of such mooring system. In addition the benefits of proper Asset Integrity Management System associated with Inspection and Monitoring programs throughout the life of the installation will be highlighted. Also identifications of some key areas will be presented, such as corrosion, where a better understanding/knowledge of the involved phenomena will lead to a noticeable improvement of Integrity. Finally the paper is going to compare variations in the design of a mooring system based on different levels of design reliability target, for two typical mooring systems in Cyclonic area.

KEY WORDS: Mooring; Design; Procurement; Installation; Inspection; Asset Integrity Management Plan; Monitoring.

INTRODUCTION

The potential environmental and economic consequences of a mooring system failure demands careful consideration and understanding of the achieved level of integrity of the mooring system in terms of strength and motion extremes.

It is clearly identified that mooring systems on Floating Production Systems are category 1 safety critical systems (Noble Denton Europe Limited, 2006). Multiple mooring line failure could put lives at risk both on the drifting unit and on surrounding installations. There is also a potential pollution risk. Research to date indicates that there is an imbalance between the critical nature of mooring systems and the attention which they receive.

The proposed paper is reviewing the various steps necessary to design, procure, transport and install a mooring system while maintaining the same level of integrity. It is no use to carefully design a mooring system while the transport or the installation may damage some of the components. Enforcing integrity is an overall process and needs to cover the whole range of such various activities for consistency purposes. Furthermore, the in-situ performance of such mooring system needs to be included in the whole integrity assessment. And proper monitoring shall be put in place.

As such the aim of the present paper is not to assess the theoretical reliability level achieved by design activities and the ways to increase such number, but to highlight the need of consistent level of care from design throughout installation activities, in order to achieve an overall satisfactory level of robustness, for permanent mooring system.

DO MOORING LINES BREAK?

Steel wire rope and chain have been used for mooring floating offshore production systems since their introduction more than 30 years ago (1st FPSO: Castellon Delta for Shell in 1976). A recent survey (Noble Denton Europe Limited, 2006) of past and presently operating FPS units has shown that serious incidents have occurred in the past, including loss of station. The survey has also shown that even for more up to date designs, deterioration of certain areas of the moorings systems may be more rapid than expected. Some of these failure mechanisms had not been anticipated during design or even envisaged, and illustrate that existing practices in design, procurement, installation and subsequent monitoring could benefit from being more robust and consistent with each other in terms of achieved integrity.

Data published by the UK HSE (DNV Industry AS, 2003) suggests an average historical rate of FPSO mooring failure about once every 7 operating years, of FSU mooring failure about once every 17 operating years, of Drillship mooring failure about once every 1.5 operating years, of Drilling Semisubmersible about once every 4 operating years, and of Production Semisubmersible about once every 8 operating years.

The following trends have been identified:

o Most failures have been associated with terminations, fairleads, connectors, pin retention details (i.e. “one off” design details not standard chain/wire elements).

o There have also been similar “one off” defects with turret systems.

o Where there have been line failures there has typically been evidence of degradation in all similar components.

o The causes have included poor detailing, fatigue sensitivity, inadequate corrosion protection, inappropriate materials and lack of adequate manufacturing process.

o Most of the failures first appeared within the first three years of
Design a permanent mooring system with the required level of reliability, several steps are necessary, whose procedures are fully captured and described in the main codes (API RP2SK, BV NI493, ISO 19901-7, DNV POSMOOR):

1. Use of the specific site metocean data
2. Use of the specific site geotechnical data
3. Derive accurate models of the floating structure including wave, wind and current properties
4. Perform mooring analysis using appropriate tools to capture extreme response and fatigue life
5. Calibrate such analysis with model tests
6. Integration of the project economical and technical limitations, and management of the various interfaces
7. Design consequently the various components from anchor to mooring hardware.

Such procedures tend to be imposed by Operators and followed by most designers.

**ADDED RELIABILITY OF MOORING SYSTEM**

Meanwhile, for some Operators, the traditional Rules and/or Standards criteria are not enough and therefore some added reliability is necessary for permanent mooring system.

The reliability of mooring system is defined as the probability that station keeping will be maintained over the n-year design life (typically 20-25 years). It is assumed that the loss of two or more mooring lines (either in the line itself or in the anchor) will lead to a loss of station keeping. Mooring system typical target reliability is $10^{-5}$; $10^{-4}$, and such target reliability levels are based upon an assessment of the functional requirements and the consequences of mooring failure.

Reasons for added reliability ($\leq 10^{-5}$) can be multiple and tend to be very dependent on the specific experience of the operator with his floating structures but also his aversion to risk. But as a prerequisite, Operators would like to continue production as long as possible and still be covered by Class and therefore insurance policy in the case of a damage mooring system, eg one broken line.

Nevertheless, in certain areas such as West Africa, the whole repair operation can necessitate up to one year – procuring, transporting & installing the new mooring line – during which the operator would like the production to be pursued safely, from an understandably economical and risk point of view. Furthermore replacement of damaged components is difficult and costly.

Several means to achieve that target are possible and overlay several steps throughout the very life of a mooring system: design, procurement, testing, transport, installation, monitoring and inspection in situ, and the use of an Asset Integrity Management system. All options are not deemed equivalent and calibration throughout comparative reliability assessment may assess their individual and associated impact.

**DESIGN OF (MORE) ROBUST MOORING SYSTEM**

The intact tension safety factor widely used by the industry is 1.67 (Minimum Breaking load of mooring component divided by Design Tension at that component) on the basis of appropriate procedures and dynamic analysis.

Typically increasing such safety factor (up to 20%) has been required when using polyester segment in mooring system, due to the lack of full understanding of their properties and lack of in situ feedback for permanently moored facilities. It is to be noted that recently this request has been relaxed by some companies as their experience in the use of such material is significant. Worth to mention that practices of increasing safety factor for FPSO structures are rather common due to the tanker based reference system, which is not fully appropriate for permanent offshore floating structure.

Means of improving the reliability of the design of mooring system have been proposed using “Response based design” methodology (Francois, Camps, Alvarez and Quiniou, 2007) or full reliability analysis (Orsero, Fontaine, Quiniou, 2007). While acknowledging the benefit of such approach, the present paper is looking at alternative solutions to achieve robust design solution.

**2 Broken Lines Compliant System**

Recently some trends have been developed by some of the Major Oil Operators to push the design of the mooring system of their floating facilities to be fully operational even with one broken line in (almost) any conditions: for the full range of loading conditions and operations (including offloading) and for the maximum design environmental conditions – typically the 100 year Return Period events. Therefore the mooring system shall be designed as such that with 1 broken line, the tension in the most loaded line shall meet the same tension Safety Factor as in intact condition: 1.67. Furthermore the 1 broken line mooring system shall meet the intact offset criteria for the riser system.

The practical consequence is that the design of the associated mooring system shall meet the damage tension Safety Factor but with 2 broken lines in any combinations, with a factor of 1.25. As such the 2 broken line mooring system shall meet the 1 broken line offset criteria for the riser system, and any other Accidental Limit State (ALS) criterion.

Basically to comply with such design requirements, mooring line(s) have to be “added” to the mooring system designed to meet the criteria of recognized standard. As an example, for a typical 3 x 3 single point mooring system, such requirement will basically lead to a 3 x 4 single point mooring system.

However such approach can be biased as the exposure of the damaged mooring system will be limited in time by its transient nature – several months to around 1 year before the full repair takes place – and therefore allowing an associated Return Period for the extreme events to be reduced to potentially 10-20 year, which in medium to harsh environment areas can reduce significantly the corresponding environmental conditions, while intuitively achieving the same level of reliability in intact (1 broken line) and in damaged (2 broken lines). Further assessment on the basis of full reliability analyses or equivalent would be required in order to give this approach a formal background likely to be accepted by Class Societies.

**Increase Return Period of Designing environmental conditions**

Some operators and/or governmental bodies prefer to specifically increase the return period of the extreme weather conditions, from the typical 100 year Return Period to up to 10,000 year Return Period, to deliberately increase the level of reliability to cope with underlying uncertainties. Such approach tends to be enforced for the design of permanent floating facilities mooring system in areas where common
practice is relying on disconnectable system. But also for area prone to Cyclonic events whose severities and occurrence have notably increased during recent years.

Also the notion of global warming factor is introduced in some operator specifications without being too precise about how to handle expected climate change and the potential impact on the specific metocean data for the selected site. It is left to the designer to decide how to integrate such factor.

**But this has a toll on cost!**

Typically a 2-broken line compliant system will increase the direct cost of the mooring system by 30-60% compared to the associated 1-broken line compliant system. Withstanding the 10,000Yr RP design condition will increase cost of mooring system by 20-50% compared with the standard rule compliant system.

In addition such systems will require additional means for installation, together with the transport of larger components.

As an example with regards to the 2 broken lines configuration versus Standard design, for a FPSO located in South East Asia to be moored by a single point mooring system in 130m water depth, the two configurations are described in Table 1, for the same level of offset criteria and type of anchor solution.

<table>
<thead>
<tr>
<th>Number of line</th>
<th>Standard (1 broken line configuration)</th>
<th>2 broken lines configuration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length (m)</td>
<td>700</td>
<td>950</td>
</tr>
<tr>
<td>Diameter (mm)</td>
<td>117</td>
<td>147</td>
</tr>
<tr>
<td>Composition</td>
<td>All chain (R4S) + excursion limiter</td>
<td>All chain (R4S) + excursion limiter</td>
</tr>
</tbody>
</table>

Another example with regards to the 10,000 year RP, for a FPSO located in Oceania to be moored by a single point mooring system in 170m water depth, the two configurations are described in Table 2, for the same level of offset criteria and type of anchor solution.

<table>
<thead>
<tr>
<th>Number of line</th>
<th>Standard (100 year RP)</th>
<th>10,000 year RP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length (m)</td>
<td>1000</td>
<td>1300</td>
</tr>
<tr>
<td>Diameter (mm)</td>
<td>127 – 115 - 122</td>
<td>152 – 135 - 142</td>
</tr>
<tr>
<td>Composition</td>
<td>Chain (R3S) – wire (spiral) – chain (R3)</td>
<td>Chain (R3S) – wire (spiral) – chain (R3)</td>
</tr>
</tbody>
</table>

**Design and Testing of Connector Elements**

The extensive use of multi-component mooring lines necessitates the use and design of tailor-made solutions to join the anchors, chains, wires, and polyester elements that make up a mooring system. Using the proper fittings, mooring components of diverse nature can be effectively connected.

Once the conceptual engineering design plans define how the equipment will be connected, 3D CAD tools are used to build the prototypes and check the interfaces among the components. It is important for offshore personnel or remotely operated vehicles to assemble and detach connectors quickly during installation. Therefore, special fittings or kits are sometimes specified.

The strength and fatigue of connectors for permanent systems need to be documented by testing and/or analysis.

**FEA** is carried out to verify the connectors’ structural integrity with an additional corrosion allowance, as required by Class Rules. The fatigue life is then assessed using the corresponding S-N curves of base material, load histograms, and the appropriate stress/load ratio obtained from the FEA.

Only after considerable testing correlated with analysis are the designs approved. After which, manufacturing drawings are generated, and then the connectors can be manufactured for use in the field.

**Design of Mooring Chain Segment**

**Fatigue:** The combined effect of tension and out of plane bending of links drives fatigue failure. Hostile environments, such as seawater, can accelerate the initiation and growth of fatigue cracks, particularly in the presence of mean tensile stresses.

**Corrosion & Wear:** The Design Rules for mooring chains all state that the protection against chain corrosion and wear is normally provided by increasing chain diameter. The allowance in chain diameter for corrosion and wear is a complicated issue that still requires significant research and service experience to address.

Often, chains are given a corrosion allowance rather than any form of Cathodic Protection. Currently industry practice is to increase the chain diameter by 0.2mm to 0.4mm per service year in the splash zone where oxygenated water tends to accelerate corrosion and in the dip or thrust zone on hard bottom where heavy abrasion/corrosion takes place.

Meanwhile typical corrosion rates from 0.5mm/year to 0.8mm/year have been observed in the relatively cold UK coastal waters. It is also anticipated that the quoted corrosion rate may not be applicable to all geographical areas and unit types. However, if the rate is even roughly correct this may well have potentially serious consequences for units intended for long term field lives. This has been the purpose of various JIP’s such as JIP Mooring Integrity, led by Noble Denton, to quantify the associated level of risk for floating units.

At present there is little data available which indicates how the break strength of long term deployed mooring components will be reduced by wear, corrosion including pitting and the possible development of small fatigue cracks. Thus it is important that this area is investigated further as a matter of priority (Fontaine, Armstrong, Potts, Melchers, Chaplin, and Francois, 2009) and a dedicated JIP – SCORCH – will test and quantify the effect of wear and corrosion on mooring chain and wire.

**Design of Mooring Wire Rope Segment**

The main mechanisms leading to wire rope degradation are corrosion, wear, crushing and wear on a winch, torsion effects, chaging and fatigue. In the majority of systems, unless fully sheathed in plastic, the life of the rope is less than that of the installation. This requires a policy of life prediction, inspection and replacement. For long term integrity it is vital that wear and corrosion are correctly accounted for in the design
process of wire rope.

The various mooring standards give recommendations for life expectancy of different wire rope constructions in terms of corrosion resistance. They also require all wires to be galvanized, and the weights of the required galvanizing can be found in codes such as ISO 2232, ASTM A856-89, etc. They identify corrosion protection measures (galvanizing, lubricant as blocking compound, sheathing, zinc anode wires) and draw attention to the need for special protection adjacent to terminations including additional anodes and electrical isolation of the rope, and the socket. Some allowance for wear and corrosion is also suggested in these standards.

Several degradation corrosion mechanisms are at work simultaneously in wire rope. Zinc dissolution arises mainly on the outer boundary directly in contact with the main fluid flow. Internal water penetration exists but minor jetting flow with rope action is expected. External and internal wear occur leading to possible lubricant migration or loss. Lubricant shielding is also expected in the inner structure as a result of confinement and low flow velocity.

Furthermore such "corrosion life enhancing" measures offered by various rope makers such as zinc wires within the rope construction may have little beneficial effect due to lack of electrical continuity within the rope construction.

PROCUREMENT & TRANSPORT

When the design activities are completed the specifications of the various components are issued to the various manufacturers. It is the responsibility of the designer to define adequately each components of the mooring system in terms of type, quality and expected Minimum Breaking Load, from anchor, chain or wire segments, connecting elements to mooring hardware on the deck of the FPU (fairlead, chain stopper, winches, windlass, sheaves, etc.). The compatibility of the various components in term of dimensions shall be carefully specified and checked. In addition, the fabrication of each component is subject to inspection and testing, as specified in Rules Requirements.

There had been mooring lines failure which were identified as induced potentially by incorrect heat treatment sequences of mooring chains (Leonhardsen, Ersdal, and Kvitrud, A, 2001). Recently a large shackle connecting a mooring system to anchoring pilings failed on an overseas floating production facility. Subsequently, an identical shackle scheduled to be used in a deepwater GOM production facility also failed catastrophically under test loads below specifications. Operator reviews of the manufacturing and testing procedure and additional material testing indicated that all of the shackles were possibly defective.

Because anchor pilings with shackles attached had already been driven, the GOM test failure required new shackles to be manufactured, new pilings installed, and the replacement of portions of the mooring systems that could not be recovered. Production start-up of the facility has been delayed by at least one year.

In a second case, two sockets in a mooring system for a MODU failed under moderate loading. Testing of the remaining sockets found that others were also defective and a number of them failed.

It has been concluded by the MMS (Mineral Management Services) that in both cases the manufacturing procedures are thought to have been defective. Heat treating after casting or forging apparently resulted in a metal unable to meet “Charpy” standards for material “toughness.” In addition, the operator’s and/or manufacturer’s specifications for the items were either out of date or inadequate. Furthermore the Operator’s material testing requirements were either not followed, or were not adequate to insure specifications were met.

To that respect, the MMS recommends the following:

- Operators should review their specifications requirements to insure testing and manufacturing produces a product that will meet the usage demands.
- Operators should include sufficient Charpy testing requirements in the specifications to ensure the materials and manufacturing process will produce a product of sufficient toughness.
- Operators should review their requirements for both destructive and non-destructive testing of critical elements. Operators should insure their test coupons are properly representative.
- Operators should review their requirements for equipment inspection and handling to ensure no damaging techniques are employed in transportation or installation.

At the same time, Class Societies have undertaken to review and update their minimum requirements as regards forgings and castings through participation to various research projects.

Worth to mention that already installed components may have been designed on the basis of insufficient or inadequate criteria, and may therefore experience premature failure. Given the potential implications of such failures, it has become essential for operators to be able to quantify the risks their floating installations are subject to. For this purpose, a Joint Industry Project jointly led by Bureau Veritas and Batelle has been set-up.

The main objectives of this JIP are:

- To develop and validate an effective Engineering Critical Assessment procedure for evaluating mooring components with industry-wide consensus. This consensus is of up most importance for the Industry to answer the Regulatory Bodies.
- To allow the assessment results for a given application to be presented as much as possible in a simple form for decision makers.
- To provide a technical basis on the specifications of new designs.

The Transport Procedures of the various components shall be carefully planned and controlled in order to reduce the risk of mishandling / damaging the components. Inspection after delivery is advised and usually is performed within the contractual agreement.

INSTALLATION

Proper Installation Procedures & Controls

The Mooring installation is high risk activity and shall be carefully planned, the various steps clearly identified, designed, checked between the installation contractor, the designer and the manufacturers of the various components. This is usually the purpose of HAZOP workshops.

Meanwhile some parameters need to be carefully looked at in order to maintain the required level of integrity of the overall mooring system already achieved in the design, procurement and transport activities:

- Anchor installation tolerances shall be carefully specified and implemented in order to reduce the risk of incorrect mooring line tensioning,
- Control of any torque introduced in mooring as is a likely point of failure,
- Way to identify properly the various steps of the installation
procedure in order to avoid mixing/swapping components, overloading segments, etc.
- Way to handle the diverse mooring components that potentially damage (partially) the component - rubbing wire rope sheath against sharp edge, dragging shackles on deck, etc. - , or loose them (drop overboard, handling rope damaged due to dynamic excitation, etc.).
- Monitoring of the various steps to control loads.

Mooring Installation Design and Analysis is essential

Time delays in getting vessel on site may require moorings to be in-situ for extended periods prior to hook up and thus must be designed to withstand conditions in the disconnected state. Achievable installation sea states need to be defined. Minimizing the need for and coordinating specialist support vessels which have limited availability is also required.

ASSET INTEGRITY MANAGEMENT

The objective of AIM for Floating facilities is to provide a management system and formalized and consistent structure to ensure continuous monitoring and action follow through to close-out on system condition and operational integrity from the viewpoints of: Safety, Environmental, Operational fitness-for-purpose, Maintenance and Quality Management.

Usually mooring AIM is incorporated within the FPSO AIM, encompassing hull structure and riser systems, and is based on information acquired during the design assessment and construction phases, providing the operator with a life-time risk-based operation, inspection and maintenance program.

Such services will use sophisticated models and Risk-Based Inspection methodologies to identify potential facility performance failures and to implement effective plans to prevent these failures. Ultimately the aim of the proposed integrity management plans will be to minimise downtime.

AIM Services Description

The proposed services will include the following steps, on the basis of models already existing for hull (Renard, Biasotto, and Lanquetin, 2006):

1. Anchoring modeling and analysis (1st assessment and subsequent periodical re-assessments)
   The mooring numerical model is based on the models derived during design activities and updated with the as-installed information, such as achieved anchors position, paid-out lengths, pre-tension, azimuths, etc.

   It is expected that a thorough survey will follow installation and hook-up of the mooring system to the FPSO, in order to identify 'stage 0' of the mooring system.

   Updated numerical models are going to be re-run and checked on the basis of the critical configurations and environmental conditions identified during design activities.

2. Qualitative RBI implementation (Risk Based Inspections)
   On the basis of the outcomes of 'stage 0' and associated design activities, and of the identifications of the critical elements/zones, inspection programs are going to be prepared and planned in order to target and inspect thoroughly those critical spots.

3. Yearly reviews of the IRM plan (Inspection, Repair and Maintenance)
   Every year the outcomes of the Inspection will be reviewed and will be used to update the mooring system numerical models. Runs will be re-performed to identify the ability of the updated systems to meet with the extreme design criteria and also with the fatigue life expectancy. Over the years, the outcomes of the inspection plans will allow deriving trends of some mechanisms such as corrosion and wear, and therefore will allow identifying the potential remaining exposure of the critical elements. Such forecasting activities are going to support and help to plan the maintenance and repair programs, by limiting their impact on production.

   It is to be noted that constant updated numerical models of the mooring system will allow the operator to conduct any exceptional analysis in an efficient manner, in addition to Emergency Response Services (see below).

4. Data management and storage (including reports)
   A proper Asset Integrity Management plan will allow the various key holders of a specific floating offshore project to have access to the various documents such as design reports & drawings, yearly inspection reports, Classification documents, yearly re-assessment reports, inspection planning (Class & others), repair & maintenance reports and planning, etc.

5. Emergency Response Services
   ERS activities can be put in place in order to have a dedicated team (Operator / Contractor / Class), and procedures to tackle in an efficient manner any potential damage such as mooring line damage. The yearly updated models will be the basis of any ERS activities.

IN-SITU INSPECTION

Finally to ensure that mooring system after their installation do behave as designed, it is necessary to perform inspection on regular basis to control the conditions of the various components. Usually the first inspection tends to take place just after the installation to ensure that the system has been installed and behaved as expected. Then global / close visual inspections tend to be performed on yearly basis for components easy to access (diver not needed) and every five years for other components. Inspection opportunities are limited, particularly in the touch down zone and at under water vessel connections. Furthermore, between the dip point and the anchor, it is generally impossible to inspect anything.

As by their very nature FPSs cannot regularly retrieve their mooring systems for inspection; their Operators have to rely on Remotely Operated Vehicle (ROVs), or occasionally diver, inspections in order to monitor any deterioration in the condition of the mooring systems. The value of these inspections, in terms of ensuring the continued integrity of the mooring system, is dependent on a number of factors that broadly speaking can be broken down into Hardware, Operational and Human Factors.

There are a number of aspects of a mooring system that need to be surveyed at a macro level in order to start building up a picture as to the current state of the system, namely:
- Gross damage
- Relative pre-tension of mooring lines
- Straightness of individual lines
- Trenching and other marks on the seabed made by individual lines
- Cathodic Potential Readings at specific points along each line
The requirements and benefits of each of these are examined in turn in the following sections. Furthermore, the needs of such inspection methodology shall be integrated into the design activities to optimise their use, while not impacting production. As such, consideration for instance to provide adequate inspection access at chain tables must be made in the design phase.

**Chain**

By their very nature, regardless of whether studded or stud-less, chains have maximum strength when they are straight (in terms of no kinks or twist or dog legs) the force being applied to them is in line with the axis of the chain i.e. a pure axial force, and the bar diameter is the same throughout the main body of the link. As a consequence, any length of chain should be checked at each survey to ensure that there are no mechanisms taking place that could adversely affect its performance.

Inspection of mooring chain by specialists shall typically investigate the presence of kinks, twists, dog legs, corrosion, wear, loose studs for studded chain, fatigue cracking and out-of-plane bending (mainly throughout excessive wear). Loose chain studs are recognized to be involved in crack propagation and fatigue of link material. Consequently, there are prescribed recertification protocols to determine the presence and the degree of looseness of studs.

There are four principal methods are currently available for chain measurement by ROV, allowing visual assessment, and they are:

- Optical equipment that requires good cleaning of chain first, work class ROV with multiple function manipulator.
- Direct measurement that can measure through most marine growth: no manipulator required. Suitable for Studless link only.
- Angled Fork: With a good manipulator and camera, this can provide a measurement of the interlink distance. Preferably it should be enhanced with centralisers to ensure correct section measurement.
- Chain Measurement by Divers using Callipers.

Inspection means that require marine growth removal may increase corrosion, and needs to be considered in the overall integrity assessment of the mooring system.

**Wire**

Inspection of mooring wire rope by specialists shall typically investigate the presence of kinks, hockles, birdcaging, twist, strands opening up, broken wires, corrosion and wear.

In addition, sockets and bend restrictors shall also be carefully inspected and each sub-component is to be surveyed considering the individual potential failure mechanisms associated with them:

- Socket Body, which can be machined or forged
- Socket Pin
- Socket Pin Locking Mechanism
- Bend Restrictor
- Cathodic Protection System

**Mooring Jewellery**

Any connection between components on a mooring line or to a fixed point on a vessel or the seabed is a potential area of integrity problems, mainly induced by the mass and mechanical discontinuities which lead to differential motion at the extremities of the element. The potential failures mechanisms have already been discussed, as they are similar to those for chain and wire, being:

- Pin Wear
- Pin Locking Mechanism
- Corrosion & Cathodic Protection
- Out of plane bending
- Fatigue

In the case of a shackle, the shackle pin, nut and split pin, if any, should also be checked for signs of significant corrosion products. Any securing device other than a split pin should be carefully reviewed as to suitability. Similarly, if the nut has been welded to either the shackle body or pin then this should also be carefully reviewed.

**Vessel Attachment**

The top end of a mooring system where it connects to a ship-shaped vessel, semi-submersible, spar, buoy or other type of floating installation is one of the critical areas of the system, as the mooring lines are likely to be under their highest tension loadings. When under water, especially for a Single Point Mooring system, it is one of the most difficult areas of a mooring system to survey, but is also an area that has seen a number of mooring system failures and general degradation mechanisms.

Consequently, it is vital that any survey of this area should be well planned and the correct type of ROV specified so that as much detailed imagery of the correct type can be obtained. An example of the difficulty of surveying in this area is hawse pipes/trumpets where to look inside them usually requires the use of a micro-ROV.

When the attachment points are located on the FPU deck, inspection and maintenance are therefore easier to perform and shall be enforced as such devices are still seeing a number of mooring system failures and general degradation mechanisms.

**MONITORING**

Finally as FPU’s tend to remain on location for periods of time longer than the ones initially used in the design of the various subcomponents, a correct assessment of their fatigue properties over the years is beneficial to the operator. Together with a monitoring of the environmental condition seen by the floating unit, the monitoring of each mooring line composing the station capability of the unit will allow to derive the range of loads imposed to the mooring line together with their frequencies.

In addition mooring line monitoring shall allow identifying almost instantaneously any failure occurring to mooring line components, without awaiting the outcomes of the planned inspection programs. Such output of monitoring system shall trigger remedial actions (inspection, safe production mode, repair, etc.) already defined and implemented in the operation procedures of the floating unit.

**Mooring Line Monitoring**

Relatively few FPU’s have tension monitoring facilities, as not required by the main Standards and Class Rules. Some of the operator’s specifications may require the need of using such devices, and leave their design and implementation to the mooring contractor. But there have been some integrity problems with some of the existing monitoring systems, and often calibration is an issue.

Some SPM units are equipped with sonar probes to visually identify
line failures from the centre of the turret but deployment is intermittent and the probes may not identify failures that occur well outboard of the turret. Excursion monitoring systems are rarely sufficiently accurate to immediately identify single line failures. Consequently a mooring line failure might not be detected for some time (especially if it initially occurred in relatively calm conditions). It is believed however that monitoring is an important part of the mooring system integrity and shall be enforced as a viable means to address life condition of mooring lines/system, in conjunction with inspection programs. Furthermore inspection of the full mooring line, from anchor to attachment point, tends to be done on a 5-years basis, leaving opportunities for other means to control the condition of the mooring system (failure of line(s), dragging of anchor, etc.) on a more regular basis.

Some monitoring methods permit a greater functionality than just detection of one or more failed lines (Oil & Gas UK, 2008). Direct measurement of tension, or measurement of angle that leads to a calculated tension, on one or more legs, may be considered an advantage in providing input data for a more in-depth analysis, together with metocean conditions monitoring. Such an analysis may be used to confirm actual behaviour that is consistent with the design, or could be used as direct input to a fatigue analysis.

The design of a mooring monitoring system should include the following features:
1. The ability to determine chain failure near attachment point,
2. The ability to determine chain failure near the catenary touchdown,
3. The ability to determine other places of chain failure by detecting reasonable changes in catenary shape near the turret.

Such system shall provide information at a time interval suitable for any remedial actions. Furthermore calibration and integrity of such devices shall be enforced and controlled on regular basis. Some redundancy may also be implemented in the various critical subcomponents. Finally they shall be designed for the extreme weather conditions to be encountered on site.

Typical monitoring systems are sonar monitoring systems and used for line failure detection.

Environmental Monitoring

The measurement of the external environment which affects the motions of the FPU and therefore the response of the mooring system is valuable to the Operators and any other concerned parties, for the following reasons:
- Building a specific database of the on site environmental conditions, to be usable for further projects in the vicinity,
- Correlating the in-situ mooring line tension measurement with the associated environmental conditions, and therefore validating the numerical modeling and assessment,
- Re-evaluating the mooring system and other critical elements, if environmental measurements over several years indicate significant deviation from the design data.

Such monitoring of the environmental conditions can be based on an on-line continuous external monitoring system such as:
- Wave Monitoring (Laser / Infrared / Radar / Wave buoy),
- Current Monitoring (Electromagnetic / Ultrasonic),
- Wind Monitoring (Anemometer),
- Mechanical Sensors.

Such devices require however precise and regular calibration to ensure proper data derivation useable by the relevant activities.

CONCLUSIONS

The purpose of this paper is to demonstrate that a reliable mooring system is not only achieved by design activities, even with extra redundancy compared with the standard requirements of the main mooring codes, but also with proper procurement, testing, installation and inspection activities.

Asset Integrity Management plans are there to measure and control the integrity level of the mooring system and its components throughout the field life, but also to plan and manage possible life extension.

Furthermore monitoring activities together with inspection will assess the condition of in situ moorings on floating production systems, and identify the trends of deterioration, and expected remaining life on the field while meeting required integrity level.

The necessary scope of condition monitoring activities shall integrate the various identified potential failure modes of the designed mooring system, using experience brought up and shared by the industry, in order to properly set up proper mooring integrity management program.

Overall it can be concluded that design to existing codes, standards and verification systems may not always guarantee the required levels of integrity because of:
- Human error leading to non compliance
- Ambiguity in the codes and standards
- Gaps in critical areas which are not adequately covered

There is therefore a place for improved guidance, however at present station keeping system integrity rests principally upon the competence of the designer, the operator, and the ICP (Independent Competent Person: Classification Society, Consultant).

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