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Integrity, Monitoring, Inspection, and Maintenance of FPSO Turret Mooring Systems

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Abstract

The long-term in-service performance of turret mooring systems is becoming increasingly important given the exponential increase in the number and complexity of FPSO facilities worldwide. The trend of floating production systems being developed in deeper waters and harsher environments coupled with longer service life requirements make the knowledge and understanding of long-term performance, monitoring, inspection, and maintenance even more important.

The paper discusses the key aspects of the long-term integrity of FPSO turret mooring systems, focusing on inspection, monitoring and maintenance of critical components of the mooring system, i.e., the anchor leg, bearing, and swivel systems. The paper provides recommendations on practical methods of monitoring and inspection of these critical components and highlights the importance of training of the operation team to ensure the recommendations are followed.

Introduction

As floating systems mature, and the deployment durations continue to increase, maintaining the integrity of an asset plays an important role in determining the useful life, and the costs associated with it. Industry codes and standards, along with Company specifications are written to provide a detailed basis and direction on design to meet the required design life, but may not adequately address the operational requirements in terms of monitoring, inspection, and maintenance with the same level of rigor.

The industry has developed a large experience base on the long-term performance of floating assets. In case of ship-shaped FPSOs this experience goes back more than thirty years. However, a lot of the learnings from operations remains "in-house" with the operators and does not necessarily find its way to industry standards or Classification Society requirements. Given the low frequency of updates to these standards it may take years for the information available to be addressed, and the guidance may not be as specific as required.

Integrity management of assets starts in the concept selection phase and continues through operation and maintenance to ensure the asset remains fit-for-purpose as it operates. In principle, integrity management aims at putting different phases of the project, i.e. concept selection, design, construction, commissioning, operation, and life extension, under one integrated umbrella and covers a wide range of topics related to these phases, e.g. design requirements, robustness, hazard identification, risk assessment, data management, inspection, monitoring, maintenance, repair, replacement, etc. It is important to ensure that a well-documented and systematic approach to this management is in place, ensuring long-term integrity and that the design and construction is conducted with long-term performance of the system in mind. This can be a challenge in the current environment where the focus is on low cost Capital Expenditure (CAPEX) and EPC contracts are now frequently decided based on the CAPEX only. Once delivered, the integrity management of the asset falls upon the asset owner who may not have the detailed knowledge of the design or the key components and is solely dependent on the Operations and Maintenance (O&M) manuals developed by the EPC contractor, and their past experience in operating similar facilities. This is in contrast to owner-operators who may lease the system and have a vested interest in ensuring the long-term integrity of the asset rather than just as an EPC system provider. Successful owner-operators ensure lessons learnt from operational experience are fed back to the design and construction phase to optimize the lifecycle costs (including Operational Expenses or OPEX) of the asset, while meeting the integrity management objectives.

The integrity management of ship-shaped production vessels within the current codes, guidelines and standards is mainly focused on two main areas - hull and marine systems, and the topsides production modules. This is primarily due to the vast experience of the industry and classification societies with oil tankers and production facilities. The guidelines have been updated over time accounting for the unique requirements for floating production systems but still remain relatively generic as they are meant to cover a broad range of floating assets and the associated equipment. In addition, there seems to be a distinct separation from a guidance perspective of design and fabrication versus integrity management during the operational phase based on inspection, monitoring, and maintenance. As examples, integrity management of floating structures is covered in two API documents, i.e. API-RP-2SIM [3] and API-RP-2FPS [1]. 2SIM was explicitly developed for fixed platforms and its direct application to floating structures is limited. 2FPS provides high level guidance on structural integrity management but lacks the detailed information required for application in practice. In recent years, the offshore industry has invested significant time and effort in developing a practical framework for asset integrity management. Some of these efforts were highlighted in a dedicated technical session on *Continued Service for Aging Offshore Infrastructure and Structural Integrity Management* at the 2016 Offshore Technology Conference (OTC 2016). For instance, Wisch and Spong [15] provide a comprehensive overview of a DeepStar project aiming at drafting the Recommended Practice for Structural Integrity Management. In addition, Classification Societies, e.g., ABS, DNV, and BV are actively developing references for asset integrity management.

The long-term performance and integrity of the anchor leg system has been subject of numerous publications, e.g. Duggal and Fontenot [6], Gordon et al. [7] and Joint Industrial Projects (JIP) like the Mooring Integrity JIP [5, 4], SCORCH JIP [12], Chain FEArs JIP [13], etc. and new approaches to monitoring and inspection of anchor leg systems are being developed, e.g,, LifeLine JIP (in progress). Regulatory agencies have also reflected on the subject, e.g., UK based Health and Safety Executive guideline on mooring systems [8] and the Oil&Gas UK document on Mooring Integrity Guidelines [10] cover a wide range of topics related to the integrity management of anchor leg systems. At the moment, recommended practices and standards on mooring integrity management are also being developed, e.g., API-RP-2MIM.

The objective of this paper is to highlight the long-term integrity, inspection, monitoring, and maintenance of turret mooring systems. Turret moored systems have an excellent record of long-term performance and adaptability to a wide range of water depths and environments. These systems, however, are made of components that are not common to other equipment on the topsides or the hull and marine systems and can be considered safety critical where their loss of integrity can have a large impact on the production performance and also possibly impact safety and the environment. The focus of this paper is on the major load transfer and fluid transfer systems of a typical turret moored FPSO. In no particular order the following three systems have been identified:

- Anchor Leg System
- Bearing System
- Swivel System

The approach recommended here is a system-based view and is in contrast to developing a component-based Operations and Maintenance (O&M) manual that just collates the inspection and maintenance required for each individual component without regards to criticality, ease of inspection and maintenance, or how it fits in the bigger picture of the (sub-) system.

General Discussion on Integrity, Inspection, Monitoring, And Maintenance

In general, integrity can be related to the ability of the system to perform its required function effectively, efficiently, and reliably. While in the operational lifecycle, the integrity of components, subsystems, and systems is evaluated by means of inspection and monitoring. From general perspective, inspection is used to assess the condition, while monitoring is used to evaluate the performance. Monitoring can be achieved by using automated instrumentation, or through tracking the results of successive inspections. As mentioned in the forthcoming release of API-RP-2MIM, monitoring and inspection go hand in hand, but are differentiated by the frequency of observation, type of feedback and the way in which the feedback is used. Inspections are typically periodic with long intervals between successive observations (in the order of months to years). They are component-based and provide a snapshot in time, on a static basis. The feedback from inspections is typically used to support longevity and fit-for-continued-service analyses and decisions. Monitoring, on the other hand, can be continuous, or with short intervals between successive observations (with a variety of time-scales). Monitoring can be used to detect sudden or gradual changes in performance, which would require further attention. The feedback from monitoring is therefore used to support day-to-day operational support and decision making, although the collective data history can be used for analysis purposes and detecting the long-term trends as well. Maintenance complements inspection and monitoring and is typically referred to regular activities required to insure the performance of the system. Maintenance is a planned activity in contrast with the repair that only happens when a failure occurs.

As indicated earlier, the focus of this paper is on specific sub-systems of a typical turret mooring system. Nevertheless, it is worth highlighting a few general notes with regards to inspection, monitoring, and maintenance of complex systems. These notes also clarify the authors' point of view when it comes to these aspects of integrity management.

Inspection, monitoring, and maintenance should not be an afterthought once the design is completed. By performing a Hazard Identification & Risk Assessment (HIRA) early in the design stage, focused on key components of the turret and with specific involvement from the operations teams, the criticality of different components can be identified by the designers and understood by the (future) operators. Consequently, sensible and practical means of inspection, monitoring and maintenance can be included in the design.

It is important to consider the operational limitations especially with the increased complexity of the floating systems today. The increased focus on inspection, monitoring, and maintenance can result in a huge demand for personnel on board the facility to perform these tasks. Operators commonly indicate that to follow the requirements of O&M manuals supplied with the FPSO, a continuous workforce of trained personnel far exceeding the typical personnel capacity of an average floating production facility would be required. Furthermore, even simple inspections or checkups requiring no more than a few minutes can become day-long exercises due to area restrictions, HSE compliance and paperwork requirements. This emphasizes the need for a risk based inspection with a focus on critical systems where loss of performance may have a large impact on production, safety or the environment. Design efforts should thus be made that allow for optimized inspection of all critical systems in a common area, using similar techniques and tools to improve efficiency. Where routine (anything more frequent than yearly), but time consuming inspections of less critical components can be replaced by automated monitoring systems, this may lead to significant time and resource savings while not compromising the assurance of integrity management. The time not spent on these small, less-critical components can be used to increase the focus on the critical components and systems. Recognizing the critical components also allows the identification of critical spares and focused training of personnel on the right components and procedures.

An effective inspection and monitoring plan should keep a balance between the visual inspection, quantitative inspections, and monitoring to help optimize the efforts. Additionally, ensuring periodic visits by expert vendor technician for critical equipment can improve the success rate of the inspection. In recent years, remote monitoring (on-shore) is becoming more common and can help reduce the work load of the offshore operating team and can streamline the data transfer.

Meaningful inspection and monitoring requires well-established baselines and long-term data recording. The so called as-built information is typically established during the fabrication, commissioning, or start-up and can significantly improve the recognition of long-term trends and changes and detection of anomalies. Furthermore, the data gathered as part of inspection and monitoring should be effectively recorded, stored, and added to the baseline. This also highlights the importance of data management as part of the integrity management of the system especially considering the large amount of data collected from design, condition evaluation, and operation. Again, a risk based approach can be used to improve the data management, data transfer between involved parties, and data presentation.

A thorough inspection needs to be followed by a comprehensive evaluation of the outcomes. The results of an inspection should be reviewed by either the original designers of the system, or suitably competent third-party experts, who may spot anomalies which could go unnoticed to the untrained eye. Anomalies of critical components should be investigated and their impact on continued operations assessed. Follow-up actions could range from increasing the inspection interval (perhaps only for specific components), to reduced operating criteria, repair or replacement.

The root cause of every integrity issue and failure needs to be thoroughly studied and the lessons-learnt should be incorporated into the operating systems, if possible, and definitely into future designs. The risk based approach also needs to be updated as new failure modes are realized and integrity issues are discovered and the inspection, monitoring, and maintenance plan should be updated accordingly.

Turret Mooring Systems

This section provides a general overview of the functionality and typical equipment on turret mooring systems to provide a reference to more specific discussions provided for each system. Turret mooring systems come in many different configurations with the three main types of systems being external turrets mounted on the vessel bow, permanent internal turret systems inserted in a moonpool at the forward end of the vessel, and disconnectable turret systems that are primarily internal but could be external as well. For the current discussion, this section will describe an external turret arrangement but the topics addressed in the paper should be applicable to all types of single point mooring systems.

Figure 1 presents a schematic of an external turret mooring system which identifies the major components. The main characteristic of a turret mooring system is that it is a "single point mooring" allowing the vessel to weathervane about a point and thus has one portion that is "earth-fixed", i.e. anchored to the earth and the other that is "ship-fixed" that rotates with the vessel. The turret serves two primary functions, (a) load-transfer between the mooring and the vessel and (b) fluid-transfer between the risers and umbilicals and the topsides. The load-transfer function of a turret is the "mooring" function of the turret and comprises the anchor leg system attached to a structure containing a bearing system that allows the vessel to weathervane. The fluid-transfer system is the interface between the SURF system (including the earth-fixed risers and umbilicals) and the topsides processing modules. The "fluid-transfer" from the earth-fixed risers and umbilicals to the ship-fixed topsides is made possible by utilizing a swivel stack system comprised of fluid, electrical power and instrumentation, and fiber optic swivels.

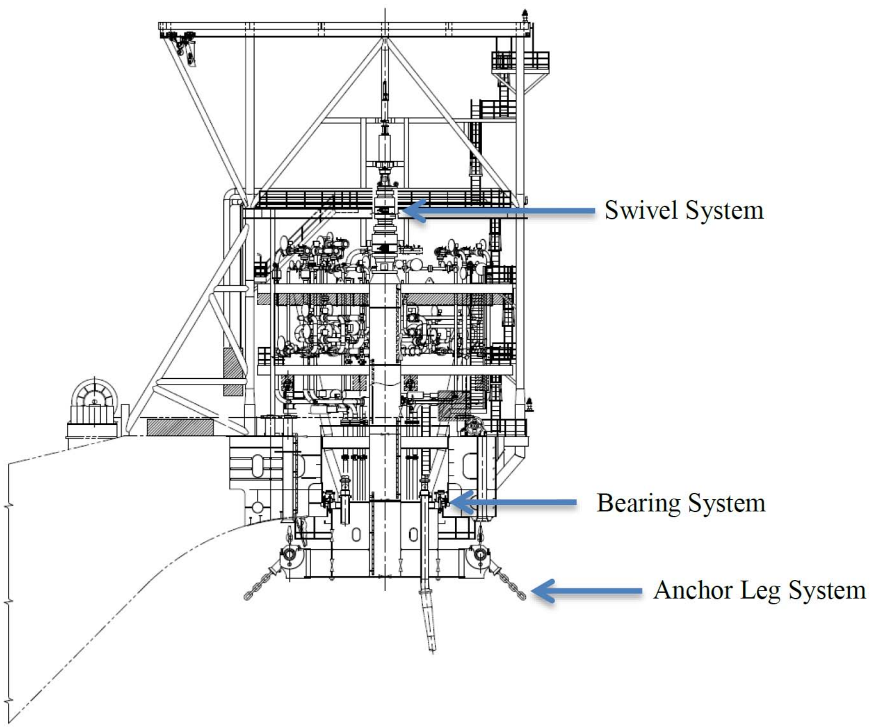

Figure 1—An external turret general arrangement

From the figure and the discussion above it is clear that there are three major systems that are critical for the operation and performance of a turret mooring system: the anchor leg system that coupled with the bearing system provides stationkeeping performance, and the swivel stack that allows transfer of fluids and signals from the earth-fixed to the ship-fixed portions of the FPSO while it weathervanes. Of these three systems the bearing and swivel systems are unique to turret mooring or single point systems as they are not typically found on other production facilities, while the anchor leg system is similar to those used in other floating facilities that are typically spread-moored.

As can be seen in Figure 1, there are a lot of additional equipment and components on the turret mooring system, some of which could be considered critical for the global system performance. These components, e.g. structural elements, piping system, instrumentation, mechanical handling equipment, etc. are however not considered to be unique to the turret mooring systems, as they are similar in nature to equipment located on other sections of the FPSO, as well as other floating platforms. It is recognized that these components require integrity management as well, but they would typically be included in the larger integrity scope of the entire facility. Thus the paper focuses on the integrity, inspection, monitoring, and maintenance of the major sub-systems that are unique to turret mooring system, i.e. the bearing and swivel system, and in a lesser extent on the anchor leg system as the industry knowledge on this topic is more mature and has been the subject of several JIPs and publications.

The Bearing System

The bearing system is the key mechanical component of a turret system that transfers loads between the earth-fixed to the ship-fixed portions of the turret and enables weathervaning. Depending on the turret type and arrangement the bearing system could consist of a single main bearing that reacts all loads and moments, or a combination of an upper and lower bearing system as in some internal turret mooring systems.

The majority of single point mooring systems utilize three-row roller bearings as the main bearing component, which are compact, self-contained systems, and extensively used in a variety of applications and industries. These bearings are typically available as continuous ring bearings up to a nominal diameter of about 8 meters, and as segmented ring bearings for diameters greater than 8 meters. The internal portions of these bearings are typically not accessible for inspection and servicing in-situ and are thus built to be robust with high factors of safety for strength, fatigue and wear. In larger turret systems the main bearing has been based on a bogey wheel arrangement or a container ring bearing system, which can be built to larger diameters and have the ability to be replaced in-situ. These bearings are typically much larger and heavier than a three-row roller bearing of the same capacity but as the majority of the components are accessible, it lends itself to direct inspection and monitoring. In-situ replacement requires proper access space around the bearing with the inclusion of mechanical handling aids in a congested area so it must be developed during the design and layout of the turret mooring system.

The rest of the discussion on bearings for this paper focuses on the inspection, monitoring, and maintenance of a three-row roller bearing and its associated components. Figure 2 presents a schematic of a typical three-row roller bearing for an external turret that shows the key components. Both the inner race (earth-fixed) and the outer race (ship-fixed) are mounted on large machined bearing support forgings to provide the required support for the bearing and to maintain deflections within the limits prescribed by the bearing manufacturer under all load conditions. The three rows of rollers indicated in red are designed to react the horizontal and vertical forces and moments exerted on the bearing. The axial support rollers react the downward thrust and moment loading, the radial rollers react the horizontal loading, and the uplift rollers react the uplift and moment loads. These bearings are bolted to the earth-fixed and vessel-fixed structures using highly-tensioned stud-bolts.

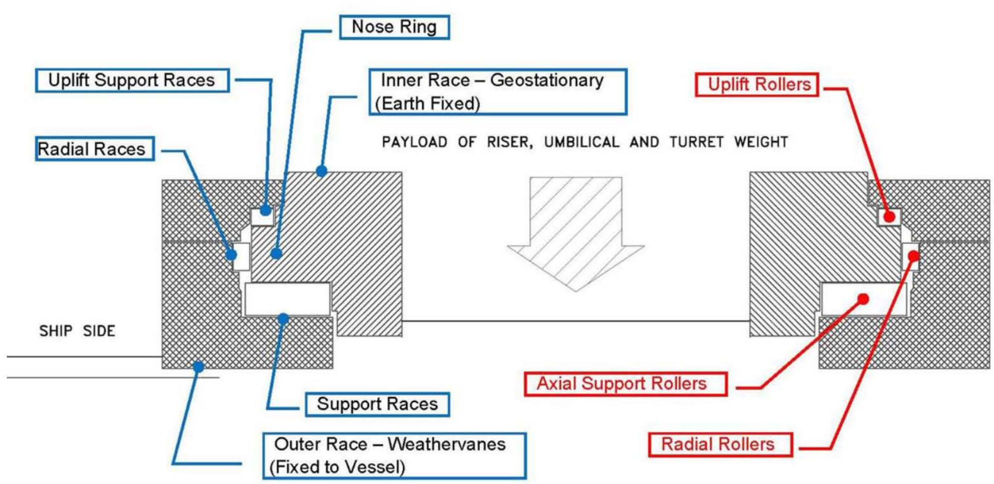

Figure 2—Schematic cross-section of a typical three-row roller bearing

Figure 3 shows photographs of a typical three-row roller bearing. Figure 3 (a) shows the axial support rollers of a bearing on the outer race before the bearing is assembled. Figure 3 (b) shows a fully assembled continuous ring three-row roller bearing, and Figure 3 (c) shows the installed bearing on the turret with the stud-bolts installed on both the inner and outer races and the stainless steel tubing of the automated lubrication system that delivers grease to the bearing. This bearing is placed in a sealed bearing housing that is also filled with grease to ensure that the bearing is protected from water ingress and debris.

Figure 3—Pictures of a typical three-row roller bearing

The automatic lubrication system is a key subsystem of the bearing and the primary system to maintain the integrity of the bearing. The lubrication system typically consists of a barrel of fresh grease, with a plunger pump and a local control panel. At fixed intervals, the pump is activated to pump out fixed quantities of grease, which is then routed through a number of metering and divider valves (both serial and parallel) and stainless steel tubing to provide grease through injection ports equally distributed to each of the races around the bearing circumference. By pumping in fresh, clean grease it is ensured that the bearing is always filled, providing another barrier against dirt and water ingress. The old, used grease is expelled through the bearing seals and relief ports to a collection area. This constant flow of grease also results in the bearing being flushed of any contaminants and debris.

The main bearing is installed in an enclosed space typically considered a restricted area, in many cases requiring a permit to enter. The lubrication system is similar, in that, it is often stored in a machinery space and then the tubing is routed through void compartments around the turret bearing. The lubrication system can be designed to automatically monitor the flow of grease through the various ports along the bearing, and to provide a fault indication on both the local panel and the Central Control Room to indicate that the system is not functioning properly.

Inspection of the bearing and the lubrication system is typically performed at well-defined frequencies (typically on an annual basis) and is measured against a baseline established right after anchor leg and riser hook-up. As part of the turret delivery acceptance procedures, 360 degree rotation tests are performed to demonstrate the performance of the turret system. This is a good opportunity to visually observe the bearing rotation and to confirm that no noise or vibration occurs within the bearing system. It is also a good time to establish the height differential between inner and outer race as a function of circumferential location for a fixed vessel heading – this should be a constant value and very close to the value shown on the drawings and the baseline measured at the fabrication yard. This relative elevation should be recorded and used as a baseline when the relative elevation is measured as part of the annual bearing inspection. By monitoring these measurements over time, changes in relative elevation can be detected, providing an indication of wear within the bearing.

Some level of wear is acceptable over the life time of the bearing and is considered within the design of the system. Deposits of wear materials are to be expected within the old grease as it is pushed out by the new grease, and therefore grease samples are to be taken during each annual inspection. Laboratory analysis can provide an elemental composition overview, indicating components were found in the old grease sample, per one of three categories: additive materials (part of the lubricant grease, which provide protection to the bearing and should match the new, clean grease composition), contaminant materials including moisture (which could contribute to corrosion inside the bearing) and wear materials (which may indicate what components of the inside of the bearing are wearing). By monitoring these compositions and their relative ratios over time, insights are provided whether the actual wear remains within, or exceeds the designed allowance.

Annual inspections require checking the stud-bolt tensions and re-tensioning if required. A full re-tensioning of all the studs is recommended once every five years. Apart from this annual inspection, which requires planning and potentially vendor representation, more frequent inspections should be performed requiring only operator observation. Spending 30 minutes once a week on the turret just observing the relative rotation between the earth-fixed and the vessel-fixed part can provide valuable insights in the performance of the bearing system. Although some minor stick-slip may be expected, the rotation should be smooth and silent. When the rotation becomes highly stuttered, vibrations occur or scraping sounds are heard, further investigation should be instigated promptly.

Further weekly inspections should include verifying that grease is expelled from the turret (and any significant changes in amount of grease monitored over time), and checking the level of fresh grease in the drum at the pump, so a near empty drum can be replaced with a full one before running dry. Given that these inspections are to be performed in areas which are often restricted or infrequently visited, it should be considered in the design stage if these checks could be replaced by automatic monitoring.

The Swivel System

The swivel system consists of swivel stack assembly, swivel support structure, swivel access structure, swivel stack support base, torque arms and torque arm support structure. The function of the swivel stack assembly is to transfer fluids, electrical power, and signals between the geostationary turret and subsea equipment and the rotating vessel equipment as the FPSO weathervanes. Other structural components provide support to the swivel stack, transfer the loads to the turret main structures, and accommodate access to the swivel stack, and their characteristics are similar to other structural components used in topside modules. The torque arms are also unique to swivel system and their main function is to react the torque generated within the swivel assembly to the swivel support structure.

A swivel stack assembly could comprise of many individual swivels. The typical types of swivels are:

- Toroidal swivel: used for production fluids, water injection, gas lift, gas injection, gas export;
- Inline swivel: the simplest fluid transfer swivel with one fluid path;;
- Utility Swivel: used for hydraulics, chemical injection fluids, utility fluids, air/gas, firewater, etc.;
- Electrical Slip Rings: used for low or medium voltage transfer and data signals;
- Electrical Power Slip Ring: used for high voltage power transfer;
- Fiber Optic Rotary Joint: used for optical communication.

Figure 4 shows a schematic view of a swivel stack with different swivel types.

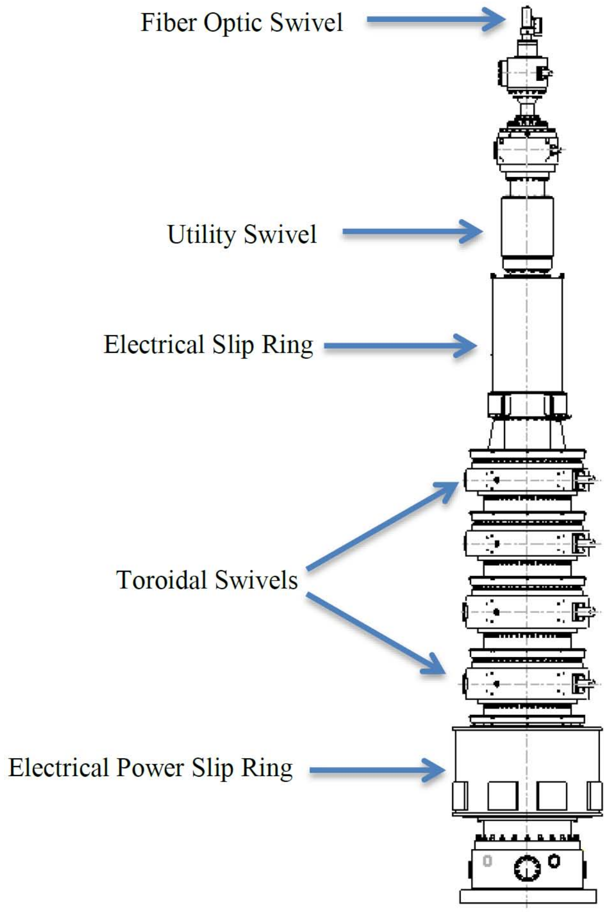

Figure 4—Schematic view of a typical swivel assembly

Figure 5 presents a schematic cross-section of a typical toroidal swivel with main components marked. The inner housing is geostationary and the outer housing is vessel fixed. A typical three-row roller type bearing facilitates the relative rotation between the inner housing and vessel fixed housing. The bearing is covered with a plate and a water seal preventing environmental ingress into the bearing race ways. One of the main components of a swivel is the sealing system. The main function of the seal system is to restrict the fluid flow to its designated area and to ensure the integrity of the fluid path. Figure 5 shows a conventional sealing system with radial barrier seals, primary and secondary internal face seals in the upper and lower dynamic interfaces between the geostationary components and the outer housing, and an extra tertiary seal at the lower dynamic interface. The seal system is designed with high level of redundancy and the seals are made from durable material tested for long-term application in severe conditions. However, occasionally, in-situ replacement of seals may be required and to ease the process, spare seals installed in between swivels in protective storage trays are provided as part of the swivel stack assembly. Another type of sealing system known as fluid barrier system is used in some swivels and is required for gas swivels. The fluid barrier system provides sealing the process fluid within the swivel by maintaining barriers of hydraulic oil captured between seals at a positive pressure above the process pressure.

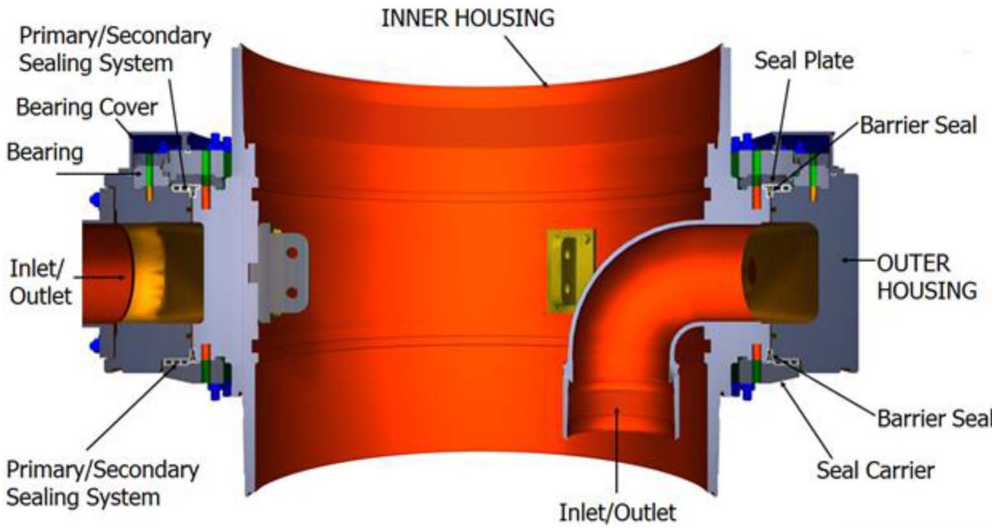

Figure 5—Schematic view of a typical toroidal swivel

The main integrity concern of a swivel system is related to the fluid containment: or in simple word fluid seepage across pressure containing seals. Defect of the sealing system is a known cause of fluid seepage in a swivel system. The swivel system is provided with a dedicated fluid recovery system which collects any fluids that escape past the seal system of the fluid swivels. Fluid from the swivels is automatically transported to the fluid recovery system reservoir through tubing and then from the fluid recovery system reservoir to the fluid recovery system pump to re-inject the fluid back into the production piping downstream of the swivels.

Similar to other structural components, the structural support of the swivel system and torque arms are subject to cyclic loading, extreme motions and accelerations, uneven load sharing, and corrosion that could impact the integrity of the system. Among all these components, the torque arm is unique to swivel system and the loads in these arms are monitored. The inspection, monitoring, and maintenance of the swivel structural components are similar to other structures on the FPSO topside and should be included in the general structural integrity management plan.

The discussions made about the turret bearing system, to a lower extent, apply to the swivel bearing. Additionally, attention has to be paid to potential ice build-up at the rotational interface due to cold environment, cold operation fluids or rapid depressurization of gas swivel that could adversely affect the rotation of the swivel bearing. The inspection, monitoring, and maintenance of the swivel bearing follow the same guidelines provided in the previous section and the associated activities of all bearings should be considered in one general plan.

The hoses connected to the swivel stack and electrical and fiber optic cables inside the swivel stack are also subject to regular wear and tear and accidental damage and their integrity should be inspected, monitored, and maintained as part of the general piping and instrumentation integrity management plan.

The inspection, monitoring, and maintenance activities specific to the swivel system are mainly related to the sealing system, fluid barrier system, and fluid recovery system. The access to the swivel system is provided through the swivel access structure and the hoists and mechanical handling equipment play an important role in easing the inspection process.

The fluid recovery system and fluid buffer system can be monitored automatically. In case of the fluid recovery system, pressure gauges are also provided in the fluid detection panel of the fluid recovery system to periodically check for fluid seepage past the swivel seals. Fluid recovery ports behind primary and secondary seals allow inspection of the status of these seals. The fluid recovery system can also be automatically monitored, providing a fault indication on both the local panel and the Central Control Room.

The level of fluid in the fluid barrier storage can be monitored automatically and a significant change of the level of fluid barrier is an indication of fluid seepage. This can be done during the visual inspection as well.

The weekly inspection of the swivel system usually includes visual inspection of the main components, torque arms, and connections for general wear and tear, loose connections, external signs of leakage, etc. Furthermore, listening to the swivel assembly during motions and change of vessel heading can help detecting integrity issues as unusual sounds and/or uneven movement may be an indication of swivel bearing or seal problems. Listening to the fluid flow or observing higher level of vibration could also provide insight about any obstruction in the flow path. As part of the weekly inspection attention has to be paid to the gauge measurements and making sure that the monitoring systems are working properly. Similar to the main bearing system, the swivel bearing lubrication system needs to be inspected during the weekly inspection.

In the quarterly inspections of the swivel system, close attention has to be paid to the end fittings, flanges, nuts and bolts, etc. Inspections related to structural integrity of the supporting structure and torque arms are also done in the planned quarterly inspections. The air pressure and hydraulic pressure supplied to or generated by the fluid recovery system and fluid barrier system should also be inspected during the quarterly inspection, but automated monitoring could be considered. Furthermore, the annual inspections of the swivel system should cover spot checking of torque in the bolts, response test of the fluid barrier system, response test of fluid recovery system, and checking the status of the spare seals.

The typical maintenance activities that occur periodically on a swivel system consists of lubrication of components, tightening of fasteners and end fittings, replacement of hoses, replacement of hydraulic filters, replacement of consumable fluid barrier, replacement of remaining fluid in the fluid recovery system. If needed, the seal in-situ change out and seal in-situ welding could be done with minimal impact on the system operation.

It is important to highlight that maintenance of production and utility swivels follows industry practices for pressure containing components and equipment used in refineries. However, maintenance of the swivel assemblies are generally beyond the training of most operators due to the complexity and size of the components and the details of the surface finishes, tolerances, and seal characteristics and should thus be performed by trained experts. Another important observation is that swivel seals can be damaged during start-up or commissioning of the associated equipment or pipelines connected to the swivel on either the vessel side (export) or the riser/pipeline side (import) due to the present of construction debris that is forced into the swivel sealing area. It is important to ensure that the system has been purged of debris before flowing product through the swivels.

The Anchor Leg System

The integrity of the anchor leg systems for permanent floating facilities has been a focus within the industry for over 10 years. This was primarily driven by the observation of premature degradation of some mooring components and unexpected failures of components on new facilities. This lead to a number of Joint Industry Projects (JIPs) and studies related to anchor leg component integrity that are available in the public domain [2, 4, 5, 6, 7, 8, 11, 12, 13]. Classification Society rules and industry standards have been updated to reflect the industry experience and well developed generic inspection, monitoring, and maintenance standards have been established by Classification Societies and Regulators. The maturity is evidenced by the open discussions held in forums and conferences where the industry openly shares its experiences with anchor leg integrity related issues and discuss lessons learnt. This has enabled feedback in to new designs with more appropriate implementation of inspection and monitoring systems and processes.

The focus of this paper on anchor leg integrity is to provide the author's philosophy to anchor leg integrity management during the operational phase, concentrating on inspection, monitoring and maintenance. A top-down approach to anchor leg system integrity management is proposed, focusing on:

- Monitoring the performance of the anchor leg system;
- Monitoring the performance of individual anchor legs;
- Inspecting the condition of anchor legs and components; and
- Maintenance of anchor leg systems and its components.

Monitoring the Performance of the Anchor Leg System

The primary function of any anchor leg mooring system is stationkeeping, i.e., maintaining safe offsets to ensure the riser system integrity for all design conditions, typically in the 100-year storm environment. Its performance is best monitored by a Global Navigation Satellite System (GNSS, typically referred to as DGPS) with reference to turret center that also provides vessel heading. These systems are robust, relatively inexpensive, provide real time data, and have a very high reliability and in the author's opinion should be required standard equipment for all floating production systems. The position accuracy is better than 1 meter at the turret center and can provide a simple means of evaluating system performance by continually monitoring the turret position and comparing that to design offset levels, e.g., with green, yellow and red offset limits commonly known as "watch circles" but may not be circular limits. Automated notifications, warnings and alarms can be generated when these limits are exceeded.

For many anchor leg mooring systems, the DGPS could be used to detect sudden changes in the anchor leg system (e.g. line break) when the mean position changes suddenly and significantly, as discussed in detail in [9], again triggering an instant warning or alarm. More sophisticated algorithms could also be developed to detect changes in system stiffness or in mean position that could provide an early warning on changes in the anchor leg system that may only be detected by a more specific anchor leg inspection that typically has a frequency of two to three years. Though this approach has not yet been put in practice it is an active area of research. The system is not that effective in assessing anchor leg condition in shallow water as the offset from one damaged leg may not be easily resolved by observing changes in mean position. This also highlights that the monitoring system as well as inspection and maintenance should be system specific and is best defined once the system characteristics are well known so the most appropriate inspection and monitoring programs are established for the operation phase of the system.

Combining the time history data collected from the DGPS system (relatively slow 2nd order vessel motions in the horizontal plane) with data collected from a Motion Reference Unit (MRU) located on turret center measuring the wave frequency vessel motions in six degrees of freedom, a fairly complete description of vessel motions can be collected [14]. Although this bulk data is of little to no use to the day-to-day decision making processes onboard the facility, it could be used as a database to compare the response of the floater to numerical models of the system that includes the anchor legs. This can be used to verify if the observed responses are comparable to the anticipated responses during the design stage, and to allow a benchmark of the existing design and to aid in life-extension studies.

Monitoring the Performance of Individual Anchor Legs

Individual anchor leg monitoring systems can also aid in installation of the anchor leg system and ensuring they are installed as designed with good load-sharing within a group. Ensuring a quantified installed anchor leg system is the first step in long-term integrity management as it ensures proper load sharing, fatigue endurance, and station keeping performance. This, coupled with the as-built survey of the anchor leg system also provides a good baseline for long-term inspection and monitoring.

Many industry codes, standards and regulations make reference to tension or load monitoring to monitor the anchor leg system and to provide line break detection. As this is a major design parameter for strength and fatigue, it is an obvious theoretical parameter to monitor and provide direct comparison to the design values. However, the industry reports that the installed load monitoring systems have had a very poor track record in terms of both performance and reliability (especially those installed underwater), and given the difficulty with replacement and re-calibration, it is the authors' opinion that such systems are not recommended for long-term monitoring of the anchor leg system.

Both the UK based Health and Safety Executive guideline on mooring systems [8] and the Oil & Gas UK issued Mooring Integrity Guidelines [10] provide detailed discussion and examples of anchor leg monitoring systems, and state that detection of an anchor leg failure is prudent. We believe line failure detection should be the primary focus of an anchor leg monitoring system, with a secondary focus on detecting uneven load sharing between anchor legs within a mooring group, caused for instance by polyester ropes stretching at different rates, or an anchor drag scenario. The focus on reliability, robustness, serviceability and the elimination of false alarms are key requirements for an acceptable monitoring system, as frequent false alarms or inaccurate data results in the data being ignored by operators, potentially ignoring a real event. Alternative parameters of individual anchor legs that can be monitored to provide line break detection and changes in tension are fairlead angle monitoring and monitoring the depth of a specific location along the catenary, typically a connector between mooring components. In the author's experience both of these measurements provide the desired feedback on performance and can be used to set warnings and alarms, when the parameters exceed defined thresholds, especially when coupled with a DGPS system. The authors have routinely used depth measurements to ensure accurate and efficient installation of the anchor leg system as depth measurements can be taken quite accurately by support ROVs and can provide a baseline for future inspections.

On external turrets, where the fairleads are above the waterline, implementing a hardwired angle monitoring system on the chain support assemblies is a robust and reliable method. Accessibility from the turret to maintain, repair or replace monitoring equipment when needed is relatively easily achieved. Also note that visual observations also provide information and should be combined with the daily and weekly inspections of the turret area. Below the surface, the installation of monitoring systems becomes increasingly more difficult. Accessibility and thus serviceability is one of the main concerns, and the focus should thus be on making all components extremely robust and reliable. Sensitive instrumentation must be able to withstand the harsh conditions of many years of submersion in seawater, subjected to marine growth, corrosion, continuous motion, strong drag forces and fatigue loading. Even when these components are appropriately designed for the service life conditions, it should never be underestimated how rough the installation process of anchor legs can be, and how easily this could damage sensitive equipment like monitoring instrumentation and cables.

Acoustic data communication is a good alternative to hardwiring equipment as it eliminates the electrical umbilical and allows the monitoring equipment to be mounted on the anchor leg itself, at a depth that is more easily accessible by ROVs. If these systems are being used for installation purposes it is important to ensure that sufficient time is provided to allow the installation of the modules after the anchor legs have been hooked up and before they are finally tensioned. Battery capacity introduces some restrictions on the frequency and amount of data that is transmitted if deployment durations are desired in the three to five year range. Severe weather could cause high noise levels in the water or create aeration, possibly distorting the acoustic signals and possibly reducing the availability or reliability at certain times.

Another promising alternative underwater anchor leg monitoring system is based on sonar technology, where a sonar head deployed below the chain table can detect the profiles of the anchor legs and risers distance to objects such as anchor legs and risers. Although this technology has recently been applied on an FPSO, no operational feedback has yet been provided to the industry on how well it performs in severe conditions, as the sonar head needs to be deployed significantly below the chain table, while remaining fairly rigid. The system has the advantage of being retrievable for inspection, cleaning and repairs but depending on specifications may require an extremely robust deployment system which can impact the turret design.

An approach utilized by the authors' to detect line failure and uneven load sharing is illustrated in Figure 6 below, for a single anchor leg group consisting of 4 anchor legs. Each bar represents the statistical values of a

15-minute measurement cycle of their individual angles: the circle indicates the mean value, while the other markers indicate the single and double standard deviation around this mean value. The figure on the left provides a clear indication that line #2 has a significantly slacker angle than its neighboring lines, indicating uneven load-sharing between the four lines in the group. The figure on the right shows a more extreme case, where the line angle has dropped to its extreme value (the line hangs vertically down), indicating that the line has failed. Appropriate thresholds were triggered to raise a warning (in yellow) when the uneven load sharing was detected, and an alarm (in red) when the line failure was detected. Note that this principle can be applied to other parameters which characterize the anchor leg profile as well, such as the depth of a known component below the water surface.

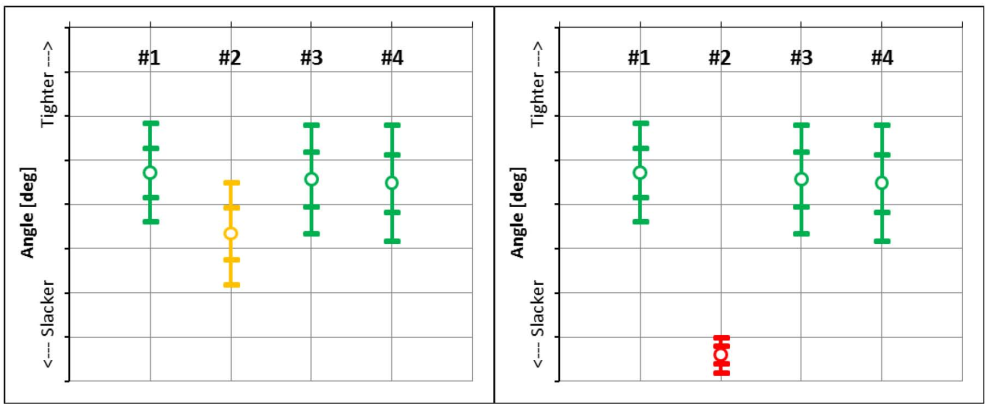

Figure 6—Visualization of uneven load sharing (left) and line failure (right)

When a loss of tension is detected by the monitoring system it is important to confirm that the trigger was in fact caused by a failure in the anchor leg, and not by a monitoring component sending out incorrect data. This could be done by monitoring the DGPS system closely to see if a shift in mean offset correlated with the failed anchor leg is detectable, or to attempt to get a visual or similar confirmation of a failed anchor leg. On external turrets this is an easy check made by going out to the turret. On internal turrets this is more difficult unless you have an ROV in the field. Alternatively the authors are in favor of a deployable camera system that can be extended through a hawse tube below the turret to allow a quick visual check on the anchor leg system. Most importantly once the line failure is confirmed, emergency response procedures need to be put in place and the root cause investigated to determine if the failure mode could be a risk to the other anchor legs. Throughout this process, the operator should continually assess (or follow procedures if the assessment was done prior) if production can continue, or if it should be suspended while the investigation is ongoing.

Inspecting the Condition of Individual Anchor Legs and Components

While monitoring is used to determine if the anchor leg mooring system and the individual anchor legs are and have been performing in accordance to their designed performance, it cannot be used to determine if they will continue to do so in the future. As mentioned in [6], all anchor leg components degrade with use and exposure to the environment. While these components are designed to allow for a certain level of degradation (typically through a site specific wear and corrosion allowance), the rate of degradation needs to be periodically verified to ensure it is lower than the design allowance. A periodical underwater inspection is typically mandatory by Classification Societies to carry out those verifications. These inspections are typically at a frequency of two to three years.

The focus of the inspection is to determine the condition of the anchor leg system and its components by comparison to the baselines established during fabrication or installation, or existing inspection data from a previous campaign. It is important that quantifiable data is taken, along with good quality video to allow assessment of the current condition, and to check for anomalies or to study particular sections identified from previous inspections or design requirements. The inspection plan should be system specific and approved by Classification Society, preferably before delivery of the system as it sets the expectation and type of data to be collected both during the as-built survey and inspections. This provides for a higher quality baseline rather than depending on the operations team or the inspection company who may not have the knowledge of the design details and critical components and/or anchor legs in terms of fatigue or strength.

Use of a practical risk-based inspection plan, based on input from the original mooring system and anchor leg designers, should lead to targeted Close Visual Inspections (CVI) of critical components, interfaces and anchor legs, rather than a complete General Visual Inspection (GVI) of the entire anchor leg system. Similarly, components can be defined which should be treated more carefully during an underwater inspection, such as polyester ropes, where a CVI the entire length and all anchor legs could actually do more damage than it would detect, due to potential contact of the flying tether and the umbilical of the ROV. Using this risk-based inspection plan, underwater inspections should be more efficient, and provide the reviewer with specific, high quality data rather than hours of low quality video footage.

Maintenance of Anchor Leg Systems and Components

The anchor legs and components are usually designed for the full design life of the floating facility with minimal maintenance. Periodic inspections and follow-up integrity analyses evaluate whether the observed and expected degradation rates remain within the designed tolerances. Sometimes though, some of these rates may exceed the design allowances, or other, unexpected anomalies are observed which could affect the integrity of one or more anchor lines. Further analysis should be performed to determine if these anomalies can be accommodated, or if pre-emptive replacement would be required. Such pre-emptive replacement would be considered a repair, rather than maintenance, which is a planned activity.

The area where the anchor leg system may need to be maintained would be the requirement to re-tension or adjust tensions to allow for better load sharing. In shallow water this may be caused by the possibility that high anchor leg loads resulted in a change in the inverse catenary in the soil or the ground chain was straightened if it was not laid out very well during installation. For deep water systems continued stretching and creep of the polyester rope segments is to be expected after the initial installation, even if pre-stretched before hook-up and initial tensioning. The rates at which these ropes continue to stretch may differ from one rope to another, and can thus result in uneven load sharing, which should be picked up by the previously mentioned anchor leg monitoring systems. It is generally recommended to investigate the need for re-tensioning after the first major storm or after every 5 years of service. It is also good practice if the anchor leg system allows to pull-up a few links through the fairlead to ensure that wear and/or fatigue loading is minimized on the critical links at the fairlead, to reduce the risk of OPB failures or wear at these locations. To ensure the ability to re-tension, it is important to inspect and maintain the pull-in system (winch, HPU, rope and sheaves) to ensure it remains functional. Feedback from the field indicates that often this maintenance was not performed, resulting in unavailability for re-tensioning when needed. Furthermore, the use of ratcheting chain supports allows relatively easy adjustment of the chain without any tug or ROV intervention.

Concluding Remarks

The focus of this paper is on the key components of a turret mooring system that are not normally addressed when discussing mooring integrity management within the industry. The emphasis is also to champion a critical systems-based approach to integrity management rather than a component based approach, which is how most Operation and Maintenance manuals are written and interpreted. For this purpose the integrity, inspection, monitoring, and maintenance of critical components of a turret mooring system are discussed and presented at a high level.

The following points highlight the main messages of this paper:

- The offshore industry is paying significant attention to asset integrity management and new frameworks are being developed to formalize the process. At the same time, asset integrity and long-term performance of the system should be incorporated into the concept evaluation and early design stages of a project and instead of focusing on CAPEX a balance between CAPEX and OPEX should be targeted.
- The inspection, monitoring, and maintenance philosophy and plan should be incorporated in the design at an early stage. It is important that field experience with similar systems is addressed regardless of whether it is required by Class or specification. Sensible and practical means of inspection, monitoring and maintenance should be included into the design. As a minimum attention has to be given to access of key components, layout of the system, and equipment handling.
- Practical limitations of the operating team onboard should be considered in developing the scope of inspection, monitoring, and maintenance. Utilizing the HIRA process, the safety critical components where loss of integrity can have a large impact on the production performance and also possibly impact safety and the environment should be identified. A risk based approach should be developed to help prioritize the process and efficiently allocate the available resources.
- An effective inspection and monitoring plan should keep a balance between visual inspection, quantitative inspections, and monitoring requirements. Where possible, automated monitoring could be applied to reduce the time spent on routine but time-consuming inspections of less-critical components. The use of remote monitoring is becoming more common and should be seriously considered in future applications.
- Following a system-based approach as a contrast to the component based approach that is commonly used in O&M manuals can streamline the inspection and monitoring process and improve the success rate of the process. It is also important to understand how the sub-systems fit in the big picture of the asset. As an example, inspection, monitoring, and maintenance of the turret main bearing system, swivel bearing system, and their lubrication system should be considered into a more comprehensive plan that is prioritized over inspection of less critical components.
- In-depth training at regular intervals for the appropriate personnel on the vessel on the inspection, monitoring and maintenance of the critical components is important to ensure that the procedures and data collection are performed correctly. Implementing a process for the vendors of these critical components to perform annual or periodic inspections is encouraged to ensure the proper procedures are followed and that training continues to ensure less of an impact of personnel turnover.
- Establishing a baseline during the fabrication, commissioning, and installation of the system is important to a successful inspection and monitoring process. Recording the outcomes of inspection and monitoring and consistently comparing the new results to the baseline provide quantifiable information on the changes and long-term trends. As an example, the baseline for the elevation of the inner and outer races of the bearing system should be defined at the fabrication stage, and just after the offshore hook-up phase, and monitoring the changes over time following successive annual inspections could provide quantitative data on the long-term performance of the bearing system.
- An inspection and monitoring process is not complete without a thorough evaluation of outcomes. Understanding the system characteristics, design margins, and criticality of the component should be considered in the evaluation process and deciding whether further actions need to be taken.
- The goals and objectives of the inspection and monitoring plan should be realistically defined. It is worth keeping in mind that a simpler approach that does the job reliably is advantageous to a sophisticated approach that is unreliable. For instance, in case of anchor leg monitoring system the main objective is timely detection of anchor leg failure and uneven load sharing between anchor

legs. While industry's focus has been on tension measurement systems that tend to be unreliable in long-term applications, other simple but more robust systems based on top angle measurement, depth measurement, relative location, etc. can be used to achieve the main objectives of anchor leg monitoring, in a reliable way.

- When it comes to inspection and monitoring, no one solution can fit all systems. A combination of different methods should be evaluated during early design stages, when an understanding of the system characteristics and failure responses are studied. A good example of this approach is used in the case of anchor leg monitoring system in which the global performance of the anchor leg system is evaluated by continuous monitoring of the turret offset, while to monitor the performance of individual legs, different approaches may need to be applied depending on the type of anchor leg system.

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