OTC-26058-MS

Stationkeeping Technology for Frontier Deepwater Floating Systems

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Abstract

This paper provides an overview of the challenges associated with the stationkeeping of floating systems in frontier deepwater, and the range of solutions to address them. The paper presents the use of existing technologies, materials and components, and compare and evaluates them to the use of novel materials, new and possibly not field proven technologies, and design approaches.

The paper provides a high-level design basis and strategies for the stationkeeping system design, identifying key drivers in the selection of the stationkeeping system. The paper then utilizes an example of an FPSO system moored in a range of water depths to illustrate the current capabilities of conventional technologies and strategies to improve performance.

Introduction

Over the past 10 years the Oil and Gas Industry has successfully explored and produced from water depths up to 2,500 meters, with the Shell Stones FPSO predicted to have first oil in 2016 in approximately 2,900 meters water depth in the Lower Tertiary region of the Gulf of Mexico. Most of the major offshore oil and gas production regions in the world have production facilities installed in water depths between 1,000 to 2,000 meters, using a variety of floating production units, riser and stationkeeping systems. This is close to the water depth typically defined as an upper bound for “ultra-deep” water (3,000 meters). Today the industry looks ahead to the next frontier which can be broadly described to have a water depth range of 3,000 to 4,500 meters (roughly 10,000 to 15,000 feet).

The success of the pre-salt fields offshore Brazil (2,000 to 2,500 meters) has led to a lot of interest in deepwater for both the Eastern and Western Atlantic area ranging from Guyana to Uruguay in the Western Atlantic and Ivory Coast to Angola, and even Namibia and South Africa in the Eastern Atlantic. In addition, frontier deepwater regions have been identified in the Western Gulf of Mexico (maximum water depth of 4,400 meters) and offshore Eastern India, and Malaysia. Currently exploration is planned / ongoing in water depths of 3,000 to 4,000 meters in many of these regions.

The objective of this paper is to take a high level view of the challenges associated with stationkeeping in these frontier deepwater regions, and to identify the key drivers that can impact the selection and performance of the stationkeeping system. The main function of the stationkeeping system is to provide offset control for various design environmental conditions, based on the requirements of the riser and umbilical system to stay within certain excursion envelopes specified. This ensures the integrity of the riser system and allows for safe operation of the unit. The emphasis on stationkeeping design is to ensure sufficient redundancy is provided so that as a minimum a single point of failure does not result in exceedance the design offsets, and that failure would not result in an “unzipping” of the mooring system, leading to catastrophic failure.

Two major items that have a significant impact in the selection of the stationkeeping system and its performance requirements are the host floating production facility and the riser system that is utilized. As can be seen in ultra-deepwater a range of systems have been utilized successfully from Tension Leg Platforms at the lower end of the water depth range to Spars, FPSOs, and Semisubmersibles at the deeper range. Looking ahead to the frontier deepwater regions identified, it is expected that the majority of the systems will utilize an FPSO, or in some cases an FPSO/FSO in combination with another production facility. The Gulf of Mexico may be an exception as Semisubmersibles and Spar production systems have been successfully deployed in water depths up to 2,500 meters.

Though a number of the topics discussed in this paper, are applicable to all moored floating systems, the focus of this paper will be in stationkeeping systems for FPSOs that lend themselves to a wide range of stationkeeping technologies and strategies, as well as various riser systems. Other papers in this session address specific aspects of semisubmersible and spar design [D'Souza, et al., 2015], and riser system performance in frontier deepwater [Sagar, et al., 2015].

Stationkeeping Technology for FPSO Systems

FPSOs have been used extensively by the offshore industry for over three decades with water depths ranging from approximately 20 meters to 2,500 meters. From a stationkeeping perspective the FPSOs can be identified as either spread moored or single point moored. A spread moored FPSO is moored in a similar fashion as the other floating systems with mooring legs at each corner of the vessel to maintain position and heading of the vessel. The majority of the single point moored vessels are turret moored which includes the connection points for all the anchor legs and the risers mounted within a bearing supported structure. The turret mooring system allows the vessel to weathervane around this rotation point, while transferring fluids and signals from subsea to topsides and vice versa using a swivel system. The weathervaning ability of a turret mooring allows for optimized environmental loading on the FPSO hull as well as high availability for offloading. In general in the same environment, the stationkeeping system for a turret moored vessel would typically have fewer anchor legs with smaller components than an equivalent spread moored system, for the same extreme offsets. England, et al. [2001] provides a comparison between spread moored and turret moored FPSOs.

Turret Mooring Systems

Turret moored FPSOs have been utilized in water depths of approximately 40 meters to 2,500 meters with one currently under fabrication to be installed in approximately 2,900 meters. They are considered to be the most versatile of all the floating production systems given the range of water depth, environmental conditions, and production rates and have been installed in every major offshore production region in the world. Turret technology has also developed to allow for rapid and safe disconnection of the mooring and riser system to avoid extreme storms or icebergs, or to allow the assistance of thrusters to align the vessel with the waves or to reduce environmental loading.

In most cases the turret is located near the bow of the vessel, either externally using a cantilever arm or internally within a moonpool in the vessel hull. All communication between the subsea systems and the vessel flows through the turret making it both a mooring system (load-transfer) and fluid-transfer system. Figure 1 presents a schematic of an internal turret that identifies the major components and equipment that is located on the turret mooring system.

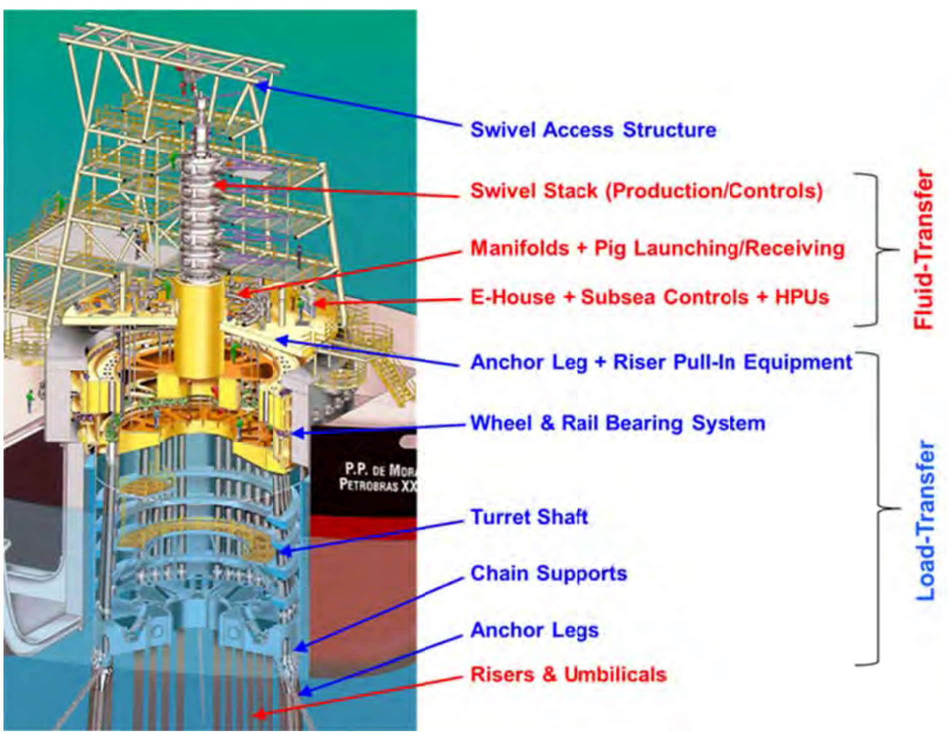

Figure 1. Schematic showing Main Features of an Internal Turret Mooring System

One main characteristic of an FPSO is the higher motions compared to the other two major deepwater production facilities – the Spar and the Semi-Submersible. These motions, especially pitch and heave, occur at the wave frequencies and the vertical motion due to the combined pitch and heave at the turret location can be quite pronounced in harsh environments. This results in large dynamic loads (both extreme and fatigue) on the anchor legs, in addition to the slow-drift motions experienced by all floaters. This is an important point to consider when using stiffer materials for the stationkeeping system for FPSOs.

FPSOs have been used extensively in cyclone or hurricane regions for over two decades with an excellent track record. The majority of these systems have been designed to be disconnectable, allowing for a rapid disconnection within 6 to 12 hours and to reconnect once the storm has passed. For these regions using this approach also puts less demands on the stationkeeping system as it does not need to experience the 100-year cyclone or hurricane conditions with the FPSO attached, and on the riser system as it does not need to experience large offsets coupled with extreme wave frequency motions. In the Gulf of Mexico the design seastate for the FPSO connected has a significant wave height of 8 meters compared to the 100-year hurricane with significant wave height of 15 meters. The trade-off is that the buoy that disconnects with the mooring and risers needs to be sized to provide sufficient net buoyancy to support the mooring and riser systems at typical depths of 30 to 70 meters below mean water level (MWL). These systems usually require integrated engineering between the turret mooring system and the riser system to ensure an optimized system.

In hurricane or cyclone environments the disconnectable turret mooring system provides a means of optimizing the capacity of the stationkeeping system and also reduces the requirements on the riser system as they do not remain connected to the vessel in the 100-year environment. Hybrid riser systems are a complementary system to this stationkeeping technology as the payload on the turret is similar with increases in water depth as the majority of the riser weight is supported by an independent structure as described in a later section. The use of a hybrid system limits the impact of riser content density to that contained in the flexible jumpers thus minimizing the impact on disconnected buoy depth.

Dynamically Positioned FPSOs

Dynamic positioning is another stationkeeping technology that is suitable for FPSO systems, and would seem to be an excellent option for stationkeeping in the range of water depths being considered in this paper. This technology has already been applied to deepwater drill ships for several years, with the latest generation of drill ships being capable of operating in 3,000 meters of water, and remains on station in 10-year hurricane conditions. These drill ships also have hydrocarbon processing and storage capability up to 15,000 bbls/day.

The MV Seillean was used as a dynamically positioned production vessel in the North Sea for 8 years and then relocated to Brazil in a water depth of almost 1,900 meters. In addition, a number of dynamically positioned FPSOs have been used as well test systems, or early production systems in various locations in the world [Lovie 2009]. Currently the Helix Producer is the first dynamically positioned FPSO in the Gulf of Mexico with a disconnectable riser buoy that is also supported by a light mooring system to provide stationkeeping for the risers once the riser buoy is disconnected from the vessel.

Thruster-assisted mooring systems for FPSOs have been used for almost twenty years, with a number of facilities in the North Sea having center mounted turrets that require heading control to provide the desired weathervaning ability. FPSOs like the Terra Nova FPSO were designed with thrusters to allow for disconnection, sail away, and reconnection to the buoy without support vessels, and these thrusters were also used to provide heading control and some offset reduction in the extreme storm conditions. Some of these FPSOs were designed with redundancy for the thrusters and also to allow for maintenance of the thrusters within the hull of the vessel. This allows for the FPSO to continue production while the thrusters are maintained in-situ.

Duggal et al. [2004] have discussed the study of a large dynamically positioned FPSO for the Gulf of Mexico, for water depths of 2,500 meters. This particular system was designed to produce 125,000 bbls of oil per day and to support 12 risers and 4 umbilicals with a storage capacity of 1 million barrels. The system was designed to stay on station in seastates up to the 10-year hurricane condition and have a disconnectable riser buoy to support the risers after disconnect. The study included both performance and cost estimates and one major conclusion was that the threshold from a cost perspective was for water depths around 2,500 meters. This would indicate that it could be a viable and cost effective option in the frontier water depths being considered in this paper but this would need to be weighed against the long-term reliability of such a system, and whether the regulatory environment would allow such a concept as a permanent production facility. Based on the experiences obtained in the industry, it should be effective as an early production / extended well test system that would have a relatively short deployment (say less than 7 years) compared to a permanent facility required to stay on station for over twenty years. In most cases the disconnectable riser buoy would need to have a supplemental mooring system to help provide stability to the riser system and this would negate the advantages of a pure dynamically positioned FPSO which would need any mooring system expense and installation. This approach would need to be compared to a traditional passively moored disconnectable FPSO like the Stones and Cascade and Chinook FPSOs in the Gulf of Mexico.

Key Factors Influencing the Stationkeeping System in Frontier Deepwater

In moving to frontier deepwater, the key factors that influence the selection of the stationkeeping system are similar to the drivers that influenced the decision for the existing production facilities in 2,000 to 3,000 meters. The focus here is to capture some key lessons learnt, to identify some parameters that can impact the stationkeeping system selected, and to highlight those that need better definition before finalizing the design. The main parameters discussed here are:

- Water depth, metocean conditions, and seabed details
- Floater type
- Stationkeeping design philosophy
- Riser system
- Mooring system components
- Installation requirements
- Regulatory environment

As mentioned earlier the focus of this paper will be for stationkeeping technology as applied to FPSO systems. This also serves as a good example since FPSOs have generally utilized a wide range of technologies for both stationkeeping and riser systems and a subset of these technologies have been used for the other deepwater floating systems. Thus the discussion for the rest of the paper is mainly focused on FPSO systems and the experience gained from a number of deepwater installations.

Water Depth, Metocean Conditions and Seabed Details

As described in the introduction the focus of this paper is on water depths ranging from 3,000 to 4,500 meters in various regions of the world. As many of these frontier deepwater regions are adjacent to shallower water regions in which production has occurred for several years the general metocean conditions are well known. For the Western Atlantic the environment ranges from relatively mild and hurricane regions to the North and swell dominated and stormy environments to the South with high average seastates and 100-year return-period conditions approaching 12 meters significant. Certain regions are also susceptible to large ocean circulation currents that can affect the weathervaning and motion performance of the turret moored FPSOs and also have some impact on offloading and operability.

Along the Eastern Atlantic the environment ranges from relatively benign in the North but subject to severe squalls that typically drive the maximum offsets and loads of the stationkeeping system, to much higher average waves and extreme seastates as further South off Namibia and South Africa. East India and the Gulf of Mexico are subject to high intensity hurricanes, while offshore Malaysia the seastate is best described as moderately severe. Typically wind and wave data is readily available (or can be developed) in most regions of the world, but the challenge has been the definition of the current environment (intensity and direction) in frontier regions (where minimal offshore activity has taken place) especially when influenced by the global circulation that typically needs to be developed by a measurement program in advance of the production facility design.

Another issue that needs to be addressed during the concept selection or pre-FEED phase is the proper characterization of the soil and the seabed bathymetry. Generally high resolution geophysical data is available from the exploration phase but many times the surveys are not focused on determining specific properties of the soil required for foundation design or proper layout of the mooring and riser systems until the FEED stage. At times surprises have been known to occur that cause major changes to the basis of design. This has ranged from the soil shear strength being greatly reduced from that observed in shallower water, to improper identification of canyons and unstable surface slopes that are not suitable for anchor placement and installation. In many cases the detailed geotechnical data required to size the anchors is only available once the project is in EPIC phase and lower strengths can lead to large impacts on anchor sizes and weights, and the resulting equipment required for installation. In discussing stationkeeping systems in these deep waters reducing vessel offsets can also result in large increases in anchor loads that also impacts anchor sizing.

Riser Systems

A variety of riser systems have been utilized as the industry has moved to deeper water depths and the advancements have followed two paths: extension of technologies used in shallower water, and development of novel riser designs that allow easier extension to deepwater. Typically riser systems can be defined as “coupled” and “uncoupled” systems, with the coupled systems referring to the direct attachment of the risers to the floater, resulting in the FPSO supporting the riser, while an uncoupled system uses an intermediate independent support for the majority of the riser, and then attaches to the floater using short flexible jumpers.

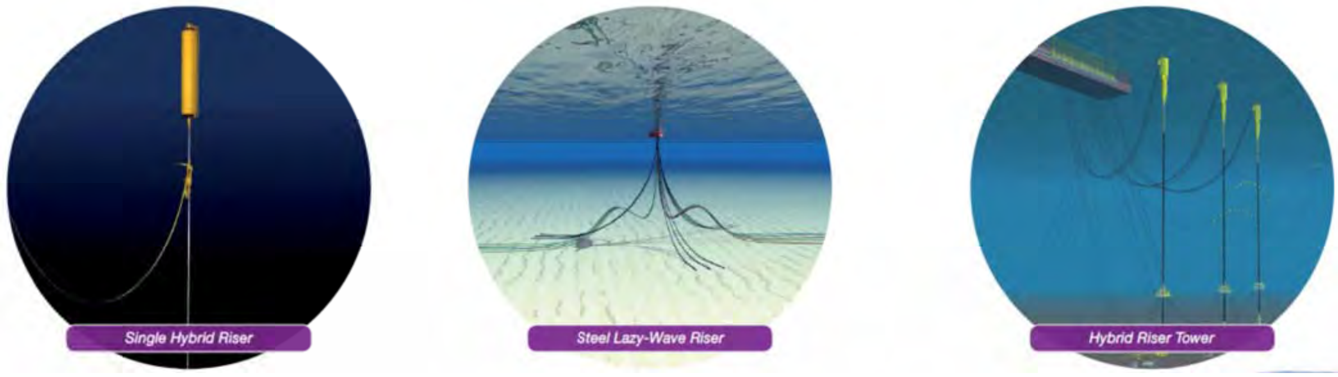

Figure 2. Coupled and Uncoupled Riser Systems (courtesy of Subsea 7)

The riser system is a major driver in the stationkeeping performance required as the extreme offsets, coupled with vessel motions, drive the selection and cost of the riser system. Typical extreme intact offsets that have been used in the design of these systems for FPSOs range from 5% to 8% of water depth for water depths of 1,500 to 2,500 meters, with the lower offset range being utilized in mild environments or where riser systems have been designed in isolation from the stationkeeping system, and the larger offsets utilized in harsher environments or where integrated design of the stationkeeping and riser system have been performed. If looking at trends in the industry, we would expect the extreme offsets required in these frontier deepwater regions to be reduced as a percentage of water depth, especially for the uncoupled riser systems. Based on our experience we would recommend that an integrated approach to the riser and stationkeeping be performed to ensure the combined system is optimized as compared to optimization performed separately as is quite common in the industry today. Petruska, et al. [2002] describes a selection process for coupled and uncoupled riser systems for a deepwater FSO in the Gulf of Mexico.

Coupled Riser Systems

Typical coupled riser systems used in deepwater are either simple catenary or lazy-wave flexible unbonded pipe or steel pipe risers. For FPSO systems simple catenary risers are utilized in mild to moderate environments, transitioning to lazy-wave configurations as the vessel motions increase. For FPSO systems the majority of the riser systems utilized are based on flexible unbonded pipe technology, though systems that utilize steel catenary and lazy-wave risers have been in production for many years, e.g. The ExxonMobil Erha FPSO offshore Nigeria, and the Shell BC-10 FPSO offshore Brazil. The Shell Stones disconnectable FPSO system will utilize steel lazy wave risers in 2,900 meters of water.

For these riser systems the increase in water depth has a number of issues that need to be properly addressed as part of the selection. As the depth increases the riser structure has to be designed to withstand higher hydrostatic pressures, typically resulting in higher weights/unit length coupled with a possible reduction in internal diameter (ID). This could be the case for flexible risers that are currently limited to water depths of about 2,500 meters in the 8 to 10 inch ID range. In addition the increase in top tension may require the use of additional buoyancy to maintain tensions and fatigue loads in acceptable ranges that may also impact the method of installation and the cost of the riser system. Another point to consider is that for a large number of risers attached to the floater the net horizontal force applied to the station keeping system is quite large and can influence the performance, layout and design of the stationkeeping system. Currently, with the deployment of steel lazy-wave risers in 2,900 meters of water depth we see that technology possibly being extended to much greater water depths. This topic is addressed in much greater detail in Sagar, et al. [2015].

Uncoupled Riser Systems

Uncoupled riser systems capture all riser designs that utilize a buoyancy module or structure to completely support the majority of the riser system and have flexible jumpers to connect from the upper portion of the supported riser to the vessel. Typically these riser systems utilize steel pipe for the majority of the riser system and the use of an independent support system and the use of jumpers effectively decouples the motions of the vessel from the steel risers, reducing the impact of dynamic loading on the steel risers. Figure 2 illustrates a number of riser systems that have been used in the industry. The most commonly used uncoupled risers systems are:

- A Single Leg Hybrid riser consists of an individual vertical steel riser supported by a buoyancy can, with a single jumper connected between the riser and the vessel. This riser type has been used in water depths just over 1,000 meters (Kizomba ‘A’ and Kizomba ‘B’ FPSOs), and the BP PSVM FPSO in 2,000 meters of water. Typical maximum intact offset requirements for this riser system are around 5% of water depth for these fields.
- Hybrid Riser Towers which consist of a bundle of risers in the form of a tower supported by a buoyancy can with flexible jumpers connected to the vessel. This riser system has been in operation for over 15 years for the Total’s Girassol FPSO, and also deployed at BP’s Greater Plutonio FPSO and the Total Clove FPSO in water depths

around 1,200 to 1,400 meters. The typical maximum intact offset for this system is around 5% of water depth as well.

- Buoyancy Supported Riser System has been recently installed at the Guara-Lula Field in 2,130 meters, connected to a spread moored FPSO. The concept consists of a large buoyancy tank tethered to the seabed with a number of tethers that is used to support up to 27 steel catenary risers. Flexible jumper hoses connect the SCRs to the vessel. The system in Brazil has been designed for a maximum intact offset of 6.5% of water depth.

In all of these systems the depth of the support buoy or upper end of the steel risers is on the order of 250 to 300 meters, positioned about 300 meters away from the floater hang-off point. The flexible jumpers are designed for offsets ranging from 5% to 7% of water depth in 1,500 to 2,300 meters of water, though the range could probably be increased by setting a different elevation and position of the support buoy system, which essentially would increase the cost of the riser system.

It is beyond the scope of this paper to evaluate the effectiveness of this system in water depths up to 4,500 meters, but the assumption is being made that the system would be installed at a similar elevation and offset location that what was used in the shallower water depths, with jumpers of similar length. In this case we should assume that the allowable offset would be around the same magnitude as what we would have for the shallower water depths so the stationkeeping allowable extreme offset would range from 3 to 5% of water depth for the 4,500 meter case. This sets a benchmark for controlling extreme offsets in these frontier water depths based on the riser system.

Anchor Leg System Components and Design

Most floating systems use a passive stationkeeping system based on anchor legs comprised of various components. In shallow water, chain in a catenary configuration is used with a large length on the seafloor, and as the water depth increases catenary moorings are based on combinations of wire rope and chain. The restoring force from the mooring comes from the catenary shape and the weight of the mooring components (geometric stiffness), and the axial stiffness of the components. Typically as the water depth approaches 1,000 meters polyester rope has been used as the primary component, typically terminated with chain at both the floater interface and at the anchor. The mooring systems are either in a taut or semi-taut configuration, with the majority of the restoring force generated from the axial stiffness of the polyester rope, coupled with some geometric stiffness from the catenary shape of the mooring. These mooring systems have now been deployed in water depths of almost 3,000 meters and typically offsets of 5 to 10% of water depth have been achieved for a variety of environmental conditions. Note that with increase in water depth and the reduction in extreme offset requirements a common approach is to increase the pretension of the mooring legs. For systems with chain at the floater – anchor leg connection point this can lead to large increases in out-of-plane bending fatigue of the top chain at the fairlead. As a rule of thumb this pretension should be limited to approximately 15% of the MBL of the top chain.

One objective of this paper is to evaluate the stationkeeping performance of conventional mooring designs for water depths up to 4,500 meters. In addition, the use of synthetic ropes comprised of stiffer synthetic fibers (as compared to polyester rope) is investigated and some general trends reported. The stiffer mooring ropes can be used to reduce vessel offset but the maximum dynamic loads and fatigue loads increase, resulting in a trade-off between offset, load and the associated costs. This is illustrated by the example at the end of the paper that studies the performance of the stationkeeping system of a turret-moored FPSO in various water depths up to 4,500 meters.

Installation Related Requirements

Installation of deepwater subsea, riser and mooring systems will probably require relatively high specification installation vessels with very large winch and crane capacity, along with large deck space and / or supply barges to install the large amounts of equipment required, especially for the mooring and riser systems. Though this is not a major focus of this paper it needs to be recognized that the cost of installation can far exceed the value of the mooring components so a major focus of the frontier deep mooring design needs to be on ease of installation rather than to minimize component costs. This could require utilizing stiffer, more expensive fiber ropes for the mooring system for offset control (with components of higher MBL to account for the higher loading) rather than increasing the number of legs with less expensive components as an example. In addition from a mooring integrity perspective the system should be designed to allow for easy adjustment or replacement of a mooring leg to offset the large cost of using high specification vessels in remote regions intervention and support activities.

It is well documented that lifting and lowering operations in deepwater can result in large amounts of dynamic amplification as well as loading on the crane / winch systems and will require detailed analysis and engineering to ensure compatibility of existing equipment to operate efficiently in these water depths. Bruschi, et al. [2015] should provide additional details on some of the challenges and requirements for frontier deepwater installation.

Permanent Mooring Systems for Frontier Deepwater

Mooring systems in 4,500 meters of water will probably be required to have relatively small offsets as a percentage of water depth compared to systems currently installed in 2,000 to 2,500 meters. Typically for anchor leg systems offset is controlled by using heavy catenary mooring systems in shallow water to taut-leg systems utilizing synthetic fiber ropes in deepwater. Offsets in deepwater can be controlled by increasing the pretension of the anchor leg, using stiffer mooring components, or using a larger number of legs. Increasing pretension / stiffer mooring components can result in higher loads on the system and also increased fatigue damage, while an increase in the number of anchor legs can increase the total cost of installation. So the mooring design needs to evaluate all of the options above to develop the optimum stationkeeping performance.

One of the strengths of using polyester rope over steel wire rope in water depths up to 3,000 meters is that the low axial stiffness of the rope, the large extension to failure, and the low weight in water allow good offset control without resulting in high loads or fatigue damage. In addition the long-term performance of polyester rope is exceptional compared to the traditional steel wire and chain components, with minimal loss of strength after 15 years of service.

For water depths approaching 4,500 meters there are probably situations where polyester is too compliant to provide the desired control unless the pretension is increased to where maximum mooring loads and fatigue damage become an issue. One alternative that has been proposed is to use synthetic ropes with a higher axial stiffness, using fibers like HMPE (Dyneema), Aramid (Kevlar) and Liquid Crystal Polymer (LCP, Vectran) in place of polyester rope, or use segments of these ropes in series with polyester segments to develop an optimum stiffness.

This section will provide a summary of the performance of the high modulus fibers and provide some information of their suitability for deepwater mooring. The last section will use an example of a turret moored FPSO in 4,500 meters of water to demonstrate the stationkeeping performance of polyester mooring systems versus mooring systems utilizing high modulus fiber ropes.

Synthetic Fiber Ropes

Polyester Rope

Polyester rope is now commonly used as a mooring component for deepwater moorings, typically exceeding 1,000 meters in water depth. Polyester rope was first studied in detail as a permanent mooring component in the early 1990's [Del Vecchio, 1992] and first utilized in the mid 1990's offshore Brazil. By the early 2000's polyester rope had become a mainstream component for deepwater moorings as it was quickly recognized as an enabling technology to effectively provide stationkeeping performance in deepwater, and has been shown to have an excellent track record of long-term integrity, especially compared to the traditional chain and steel spiral strand components.

Compared to steel spiral strand wire, polyester rope has a much lower weight in water, a lower axial stiffness, and much higher tension-tension fatigue life, allowing it to be used effectively in taut-leg mooring systems. Its low weight results in relative low pretensions of the anchor leg system compared to that used with wire, and its low stiffness results in reduced extreme and fatigue dynamic loading in the anchor leg system (including the anchor) and thus on the steel components which are more susceptible to fatigue damage. In addition its low weight makes it much easier to install, and as long as the installation is properly engineered and equipped to install the polyester system, it can be installed safely and with minimal risk of damage. Polyester ropes recovered after 10 to 15 years of service have shown minimal loss of the design MBL and no noticeable degradation of the cover or splices. It should also be noted that polyester fiber is now a commodity with a very large capacity of fiber available in the market place, and thus is relatively inexpensive. If there is one negative with polyester it is that the diameter of a polyester rope with equivalent MBL of sheathed spiral strand steel wire would be 50% greater. This requires large reels for the polyester rope and in many cases the capacity of the winches on board available installation vessels limit the lengths of continuous polyester rope segments that can be used; thus requiring the connection of shorter segments of polyester rope to get the desired length. For example offshore Brazil on projects for PETROBRAS, the installation vessel winch capacity is typically limited at 1,000 meters of 1,250 MT MBL polyester rope when each leg requires approximately 3,000 meters of rope.

Synthetic fibers like polyester are visco-elastic materials and do not exhibit a linear load-elongation curve like steel. The properties of both the fibers and ropes have been studied extensively by the industry over the past 20 years to provide a description of the behavior of the rope. As described in Del Vecchio (1992) the equivalent stiffness of polyester rope is a function of the mean load, the load amplitude, and to a lesser extent the period of load application. In addition, polyester fiber has a logarithmic creep characteristic, and the rope would see permanent elongation under sustained loading due to the fibers bedding in (as compared to the new rope manufactured under relatively low tension). Due to the complex stiffness characteristics of the polyester rope it should also be noted the actual stiffness seen during stationkeeping is also a function of the floating host motion characteristics, and the environment.

There are a number of standards and codes that specify tests to perform on a rope to get a set of consistent values that confirm the characteristics of the fiber, define elongation as a function of load history, and estimate stiffness as a function of mean load, amplitude, and load frequency. This is shown in Figure 3 which shows the results of a stiffness test being performed on a worked polyester rope.

It is also quite common for engineers in the industry to express the stiffness as a multiplier of the MBL of the rope. Using this approach the stiffness can range from a static stiffness of around 12 times MBL to a stiffness of up to 30 times MBL for loading of 40% to 50% of the MBL. Permanent elongation of a polyester rope when loaded to 50% of MBL for a number of cycles can be 3% to 4% of the unworked rope length. This obviously has implications in the analysis and design of mooring systems as the water depth increases. Note that polyester fiber and rope is probably the most studied material/component in the stationkeeping industry and the twenty year effort that has gone into this has resulted in improvements in rope design and termination technology to where the efficiency of the rope (based on fiber MBL) is in the order of 70% to 75% compared to around 50% to 60% when first utilized.

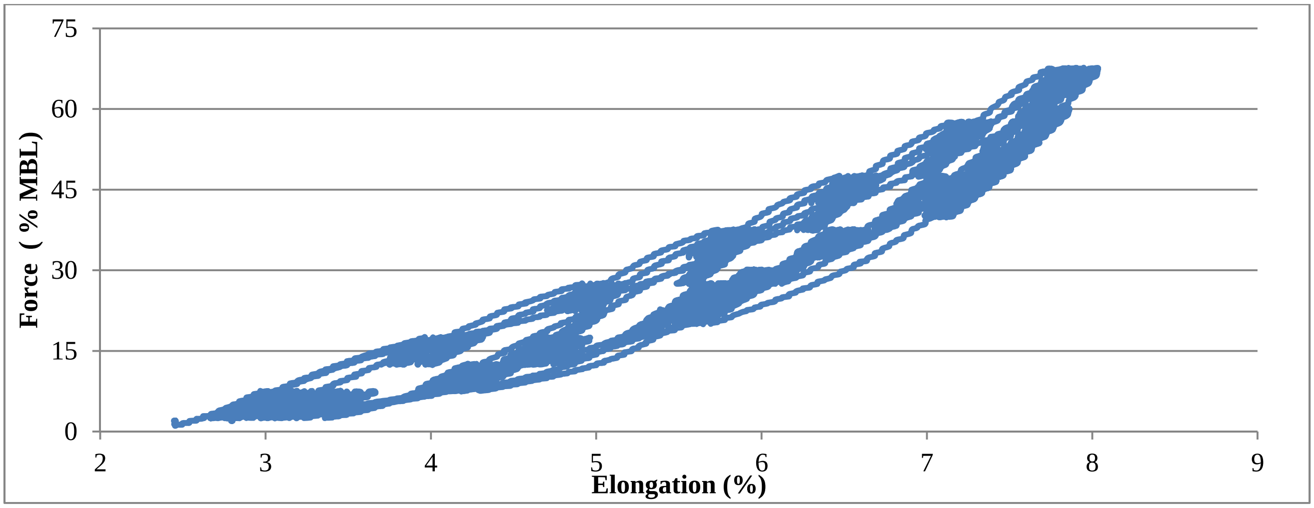

Figure 3. Stiffness test of polyester rope

All of these factors need to be taken into account in the mooring design to ensure the proper rope characteristics are used in the analysis and design of the stationkeeping system and the correct "unworked" new length ropes are specified. It is also important to ensure that proper estimates of rope elongation due to the rope being worked during installation and during the life of the field are used to ensure that the installation approach or ability to adjust length of the mooring once installed are properly specified. This is extremely important as the water depth increases where you have several kilometers of synthetic rope in one anchor leg.

High Modulus Fiber Ropes

There are a number of high modulus and strength fibers that have been developed over the years in the market and have been used in a variety of applications in a number of industries. Currently there are four fibers that are seen to have promise for the offshore industry as a stiffer and lighter replacement for polyester fiber ropes when required and are seen to have an application as we move to water depths around 4,500 meters.

To date, all permanently moored systems in ultra-deepwater are utilizing mooring systems with polyester rope combined with chain and or spiral strand wire rope. This has been seen to be effective in water depths up to 2,500 meters, and will also be deployed for the Stones FPSO in 2016. This seems to indicate that in most cases polyester rope moorings have been shown to be suitable for water depths up to approximately 3,000 meters, especially for FPSOs.

The four fibers that have been studied for use as mooring components are:

1. PEN
2. Aramid (Kevlar)
3. HMPE (Dyneema)
4. LCP (Vectran)

Of the 4 fibers PEN (Polyethylene Naphthalate) is a high performance member of the polyester family that results in an effective increase in rope stiffness of approximately 30% over a polyester rope. The other three fibers when used in rope constructions have an effective stiffness that is similar (with caveats) and range about 3 to 4 times that of polyester rope. These three fibers also have about the same weight per meter and diameter for a given break strength and for the purpose of this paper the ropes manufactured from fibers these are assumed to have the same stiffness and weight properties. However, at the fiber level the differences between the three can be quite pronounced as described in some of the references to this paper [Davies, et al., 2002, Del Vecchio, and da Silva, 2011, Huntley, 2011; and Haach, et al., 2011].

Figure 4 presents the quasi-static stiffness of a worked polyester rope and an aramid rope from [Huntley, 2011]. The load elongation curve helps illustrate the behavior of the synthetic ropes under load, and provide a comparison between the relative stiffness of the high modulus fiber ropes compared to a standard polyester rope. It is also seen that the behavior is similar for the two ropes and this is also true when studying the dynamic stiffness behavior as a function of mean load, load amplitude, and frequency. The following subsections provide additional information on the three high modulus fiber ropes and will not address the PEN fiber ropes though they are also a viable candidate.

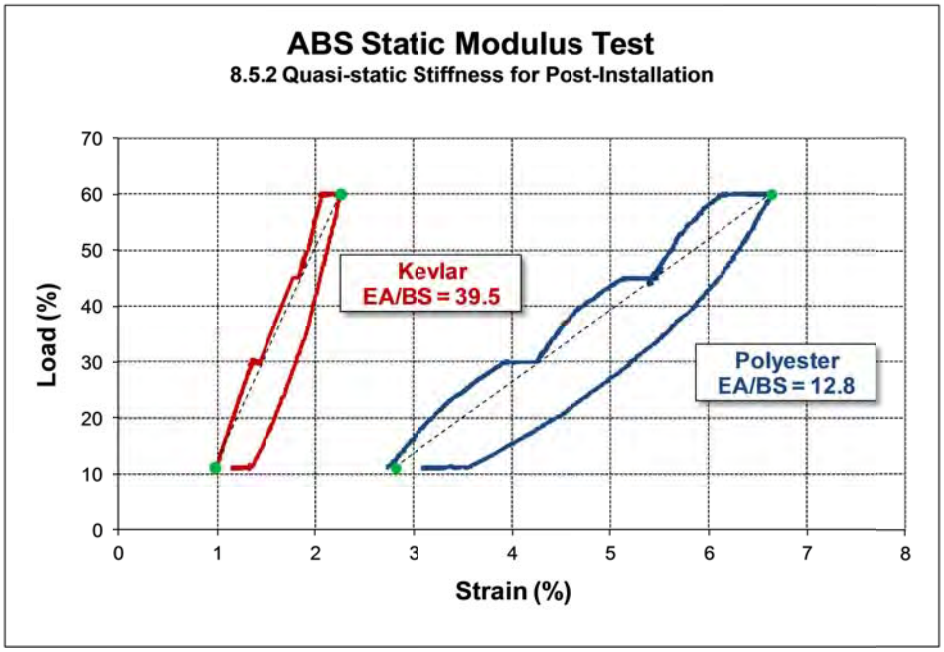

Figure 4. Comparison between Quasi-Static Stiffness of a Kevlar and Polyester Rope (courtesy of Whitehill Manufacturing).

Aramid Ropes

Aramid mooring ropes were first used in the industry as part of the mooring of a construction vessel during the installation of the Elena guyed tower in the mid 1980's. A number of the mooring lines had premature failures during the operation and the failures were studied and reported by [Reiwald, 1986]. The primary cause of failure was due to the pure compressive fatigue behavior of the aramid yarns that were determined to have kinked at several locations. The failure mechanisms were due to a combination of factors but include the fact that the rope was in the touch down zone and was in contact with the seabed obviously causing compression in that section of the rope. Failures also occurred near splices indicating that fibers were seeing compression in those areas.

Recently a number of studies and tests have been conducted on Kevlar based ropes [Chi, et al., 2009; Huntley, 2011] that show that improved finishes on the fibers coupled with improved rope construction and termination exceed the requirements of the compression test required by ABS which requires cycling the rope for 2000 cycles between 1% and 20% of MBL and having a remaining MBL greater than 95%. This combined with proper mooring design that would keep the minimum tension above 2% of MBL would make aramid based ropes a promising high modulus fiber rope alternative as it has a relatively large manufacturing capacity compared to the other high modulus fibers. Currently the cost of an aramid rope would be about 2 to 2.5 times that of a polyester rope with equivalent break strength.

HMPE Ropes

HMPE (High Modulus Polyethylene) ropes have also been used in the oil and gas industry, especially for lifting slings, winch ropes, and towing lines due to their light weight, equivalent strength to diameter ratio as wire rope, and ease of handling characteristics. The HMPE fiber is known to have very poor creep rates and creep rupture has always been a concern, especially when used in applications where a high load is applied on the rope for a long duration (say 50% of MBL for a month). HMPE ropes are typically made with three distinct fibers today: SK75, SK78 and DM20. SK75 is the fiber most people associate with HMPE and is used for work ropes but has very poor creep characteristics and is not suitable for use as a mooring rope. SK78 [Leite, et al., 2011] has been approved for MODU ropes as the creep rate is improved to where it is considered to be acceptable for most temporary applications, while DM20 [Leite, et al., 2012] is a newly developed fiber whose creep rate is dramatically reduced to a level that is considered applicable for most permanent mooring applications, but the data available for assessment today is limited.

HMPE ropes are marginally the stiffest and lightest ropes of the three high modulus fibers discussed here but the impact of creep can affect the long-term effective stiffness of the rope, especially if you consider the case of a Spar in a loop current in the Gulf of Mexico where the mean load in the rope can exceed 40% of MBL and have a duration of 2 to 3 weeks. For a typical floater like an FPSO when you look at the variation of stiffness as a function of load and load amplitude, it can be considered to be equivalent to the other two high modulus ropes in stiffness and weight for the example that is presented in the next section.

One issue that may need to be addressed for HMPE is the limited capacity in the market today for the large production required for offshore mooring ropes, especially in ultra-deepwaters. Currently it is estimated that ropes constructed from the DM20 fiber would cost 3 to 4 times that for a polyester rope with equivalent MBL.

LCP Ropes

LCP (Liquid Crystal Polymer, Vectran) is a relatively new fiber being introduced for deepwater mooring ropes. Typically the properties of this fiber are very similar to aramid but with much better axial compression fatigue and creep performance [Flory, 1992; Del Vecchio, 2011]. The rope stiffness and submerged weight per unit length is similar to the ropes made from aramids. Currently capacity is limited and costs are similar to HMPE but there is a potential for this fiber to be mass produced at a lower cost if the market demands it.

Case Study: Permanent Mooring Performance as a function of Water Depth and Synthetic Rope Stiffness

In order to evaluate the application of high modulus synthetic material in frontier deepwater mooring systems a comparative study has been performed. For the purpose of this study, an internal turret mooring system with 9 taut legs arranged in 3 groups of 3 legs is evaluated. Table 1 presents the vessel properties used here and represent a typical converted VLCC. The mooring legs comprise three main sections of top chain, synthetic rope, and bottom chain. The study is performed for three water depths (WD) of 1,500, 3,000, and 4,500 meters covering the range of current design practice to frontier deepwater areas. For each water depth, three synthetic rope configurations are considered: a) all polyester (100% Poly), b) a blended configuration with equal lengths of polyester and high modulus rope (50% Poly & 50% HM), c) all high modulus (100% HM). It is known that use of high modulus synthetic ropes is not common for water depths for the shallower water depths but was included for completeness of this study. For simplicity, a linearized estimate of axial stiffness of 18.5 times MBL is considered for polyester rope, and a value of 55 times MBL for the high modulus synthetic rope. These assumed stiffnesses are considered to be representative of the overall dynamic stiffness of the two ropes under quasi-static and dynamic loading and are thus higher than the quasi-static stiffness values, while lower than the peak dynamic stiffness values. These stiffness values tend to be conservative for calculation of extreme offset and fatigue damage while underestimating the extreme dynamic loads. It should be noted that the main purpose of this comparative study is to evaluate the trends and absolute values are not that important as the mooring systems studied are not optimized for the conditions considered here.

Table 1. Properties of the FPSO

Length	320	m
Breadth	56	m
Draught	15.5	m
Displacement	230188	mT
Top Side Weight	20000	mT
Daily production	100000	bbl/day

Table 2 presents the component lengths and general characteristics of studied mooring systems. To limit the number of contributing variables, the top chain and bottom chain segments are kept the same in all cases studied. Following the same idea, at each water depth, the top tension and mooring horizontal radius are kept constant for different synthetic rope configurations, i.e. only synthetic rope length, mass, and stiffness are varying. As can be seen in Table 2, the pretension has increased from 180 MT for the 1,500 meter water depth to 200 MT and 225 MT respectively for 3,000 meters and 4,500 meters water depths. The increase in the pre-tension as a function of water depth is considered for more consistency in the mooring system stiffness and is considered reasonable for a mooring system with components of approximately the size assumed. For out-of-plane bending fatigue of top chain, it is recommended to keep the pre-tension to less than 15% of MBL which is maintained in this study.

Table 2. Mooring System Components and Properties

Section	Description	1500m WD			3000m WD			4500m WD		
		100% POLY	50% POLY - 50% HM	100% HM	100% POLY	50% POLY - 50% HM	100% HM	100% POLY	50% POLY - 50% HM	100% HM
		Segment Length [m]								
Top Chain	Studless Grade R4 - 130mm Dia.	150	150	150	150	150	150	150	150	150
Synthetic Rope	Polyester	2100	1052	-	4000	2003	-	6300	3158	-
	High Modulus	-	1052	2107	-	2003	4014	-	3158	6334
Bottom Chain	Studless Grade R4 - 130mm Dia.	225	225	225	225	225	225	225	225	225
		Mooring Leg Properties								
Horizontal Radius [m]		1982			3215			5005		
Top Tention [mton]		175			200			270		

In Figure 5 the restoring force curves as a function of normalized offset are presented. These curves are generated by applying a static force to the mooring system and determining the offset as the load increases. As indicated earlier in this paper, the stiffness of a taut mooring system is mainly dominated by the axial stiffness of mooring components, with some geometric stiffness from the catenary configuration of the legs. This can be clearly seen by comparing the slope of the curves for different synthetic rope configurations shown in Figure 5. For instance, the mooring system with all high modulus in 4,500 meters of water depth is almost 3 times stiffer than the mooring system with all polyester. This indicates that based on static loads the high modulus system is effective in reducing offset as expected by its high axial stiffness. In general, as water depth increases the mooring system stiffness decreases due to longer synthetic rope segments. However, the mooring system stiffness changes almost linearly with water depth due to linear increase in the length of synthetic rope. This can be realized by comparing the curves of the same rope configuration in different water depth. The significance of this observation is that the same synthetic rope configuration will have a similar offset performance in different water depths.

To evaluate the dynamic characteristics of the mooring systems a comparative study is carried out. Different aspects of dynamic analysis including regular motion analysis, extreme analysis, and fatigue analysis are evaluated. It should be mentioned that a detailed modal and dynamic analysis of mooring system is not in the scope of this paper and only some general trends are highlighted here.

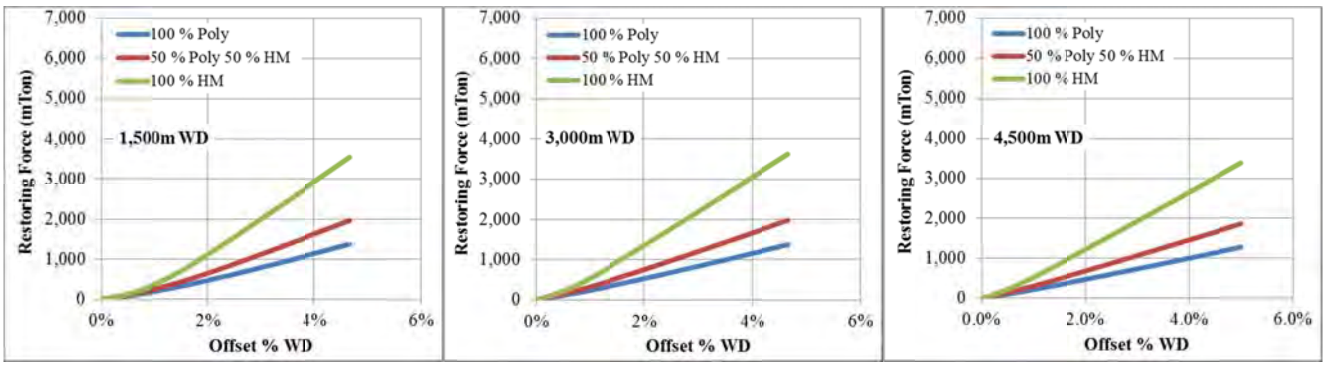

Figure 5. Restoring Force curves as a function of Normalized Offset

The dynamic analysis has been started with performing a simple parametric analysis using regular motions. For this purpose, the top end of mooring leg is oscillated vertically with 1 meter amplitude and periods ranging from 8 to 12 seconds. The amplitude of mooring leg tension at the fairlead and anchor are summarized in Table 3. As expected, the mean tension reduces along the mooring leg. A general trend seen in the results presented in Table 3 is that dynamic load amplitude reduces as the mooring leg stiffness decreases. This means that using stiffer material may translate to higher extreme loads and fatigue damage. Another point worth mentioning is that the dynamic load amplitude tends to increase from fairlead to anchor. This phenomenon is more pronounced in softer systems, e.g. 100% POLY in 4,500 meters water depth. This indicates that for soft systems the most critical point for tension-tension fatigue may not be the top chain. More discussion on tension-tension fatigue of mooring chain components is provided later in this section.

Table 3. Tension Amplitude in Regular Motion Analysis - Heave Amplitude of 1 meter

Synthetic Rope	Loc.	WD = 1500m			WD = 3000m			WD = 4500m		
		Amp (T) - [mton]			Amp (T) - [mton]			Amp (T) - [mton]		
		T = 8sec	T = 10sec	T = 12sec	T = 8sec	T = 10sec	T = 12sec	T = 8sec	T = 10sec	T = 12sec
100% POLY	Fairlead	8.5	7.3	5.5	2.5	3.6	3.7	4.2	2.1	2.0
	Anchor	10.4	7.9	5.9	6.8	5.6	5.1	6.5	5.0	4.3
	Ratio	1.2	1.1	1.1	2.7	1.5	1.4	1.6	2.4	2.1
50% POLY 50% HM	Fairlead	13.3	9.8	6.8	5.6	6.3	5.5	2.1	3.0	3.6
	Anchor	14.0	9.8	6.8	8.9	7.8	6.6	6.9	6.0	5.6
	Ratio	1.0	1.0	1.0	1.6	1.2	1.2	3.3	2.0	1.6
100% HM	Fairlead	19.7	11.9	7.6	13.8	11.2	8.2	7.2	7.7	6.6
	Anchor	18.8	11.2	7.4	16.0	12.1	8.9	12.0	10.4	8.6
	Ratio	1.0	0.9	1.0	1.2	1.1	1.1	1.7	1.3	1.3

In the next step, a set of extreme analysis are performed for a relatively severe storm condition with significant wave height of 13 meters, peak period of 14 seconds, a 1-hour average wind speed of 36 meters/second, and a surface current speed of 1 meter/second. The global analysis is conducted for co-linear wind, wave, and current approaching the mooring system in-line with a mooring group and in-between two mooring groups using a fully dynamic frequency domain calculation. The statistics of interest are the most probable maximum (MPM) vessel low-frequency offset (includes the mean offset), and the most critical MPM mooring leg tension in a 3-hour storm. The results of these analyses are summarized in Figure 6. For easier comparison the offset is normalized with water depth and the factor of safety (FOS) is calculated as the ratio of MPM tension to minimum breaking strength of synthetic rope (1,300 MT). As expected and shown in Figure 6, the softer mooring system experiences larger vessel offset. For instance, the all polyester mooring system in 4,500 meters of water experiences almost double the offset of the all high modulus mooring system. Interestingly, for all configurations as water depth increases the offset to water depth ratio decreases. In the case of the all polyester mooring system the normalized offset reduces by about 35% from 1,500 meters to 4,500 meters water depth. This illustrates the natural reduction of the dynamic offset with an increase in water depth due to overall system damping and the natural period of the system that is not accounted for when making a simple static force and resulting offset calculation that is commonly made when comparing the performance of high performance ropes to polyester rope moorings.

Also from a dynamic analysis perspective the trade-off for lower offsets by using a high modulus rope is that the maximum dynamic mooring leg tension increases as the anchor leg stiffness increases. As can be seen in Figure 6, the FOS of mooring system with all polyester is about 25% higher than that of mooring system with all high modulus synthetic rope. Similarly, as mooring system gets softer for the higher water depths, the maximum mooring leg tension decreases even though the pre-tension is increased with water depth.

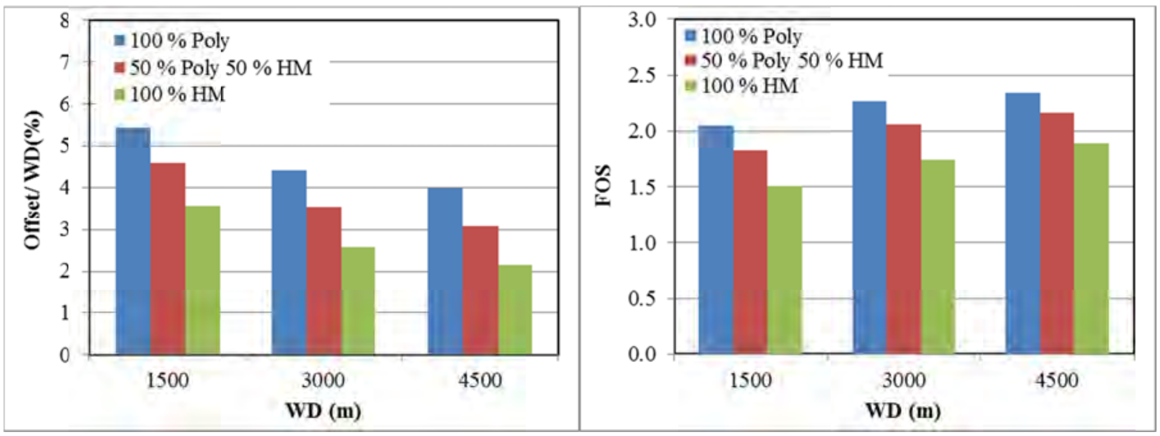

Figure 6. Results of Extreme Analysis

To complete the dynamic analysis, the tension-tension fatigue performance of the mooring systems studied is compared using a simplified fatigue analysis. For this purpose a representative set of fatigue cases consisting of 14 seastates is developed. The list of these load cases are provided in Table 4. The fatigue cases are defined with wind direction being in-line with one mooring group. The analysis is performed in the frequency domain and the contribution of wave-frequency and low-frequency tension components are combined using the API formulation of Combined Spectrum with Dual Narrow Banded Spectrum [API RP2SK, 2005]. The fatigue damage of the mooring chain components is calculated using the API T-N curve. A summary of the fatigue factor of safeties (FOS) at the fairlead and anchor is presented in Figure 7 where the fatigue FOS is calculated as the ratio of fatigue life by the assumed mooring system design life of 20-years. As clearly shown in this figure, the fatigue life of the chain is significantly reduced as the overall synthetic rope stiffness increases. Following the same trend, the fatigue life increases as with the increase in water depth (due to the compliance of the synthetic section. As discussed earlier, the dynamic loading tends to increase from fairlead to anchor and that also results in considerable fatigue life reduction in the anchor chain as compared to the top chain.

Table 4. Fatigue Seastates

LC	Primary Wave			Secondary Wave			Wind data		Current data		Prob.
	Hs (m)	Tp (sec)	Dir (deg.)	Hs (m)	Tp (sec)	Dir (deg.)	Ws (m/sec)	Dir (deg)	Vc (m/sec)	dir (deg)	
1	2.22	6.8	195	0.82	7	131	9.8	180	0.24	220	5.2%
2	2.09	6.9	180	0.86	8.3	102	9.9	180	0.27	206	26.0%
3	1.99	6.7	165	0.76	8.1	101	9.7	180	0.27	195	21.2%
4	1.87	7.1	150	0.63	5.3	141	8.2	180	0.26	199	10.1%
5	1.68	8.6	135	0.41	4	204	5.7	180	0.24	205	5.4%
6	1.57	8.7	120	0.6	4	192	5.8	180	0.28	211	4.7%
7	1.55	9.2	105	0.74	4.1	176	5.8	180	0.28	195	5.5%
8	1.6	10	90	0.84	4.6	175	6	180	0.26	212	4.8%
9	1.82	10.9	75	1.03	4.7	172	6.7	180	0.29	211	4.5%
10	1.97	11.6	60	1.08	5.1	168	7.2	180	0.28	215	4.6%
11	1.99	11.8	45	1.09	4.9	168	7.1	180	0.24	216	3.4%
12	2.21	12.1	30	1.06	4.9	170	7.2	180	0.23	194	4.1%
13	2.25	11.4	15	0.96	4.3	188	7	180	0.19	239	0.5%
14	1.74	6.6	300	0.51	4.5	218	4.7	180	0.21	227	0.1%

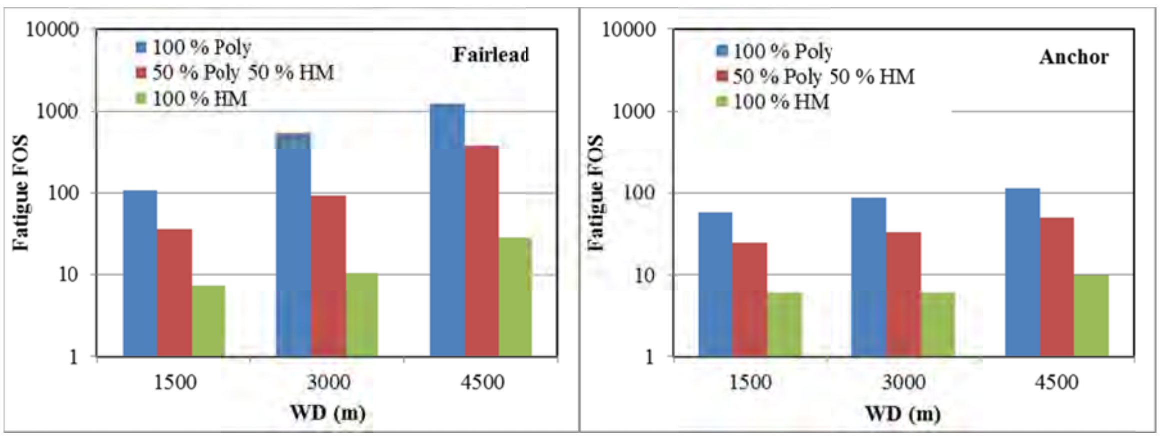

Figure 7. Results of Fatigue Analysis

Application of high modulus synthetic ropes in mooring systems can be used to control vessel offsets, especially in the frontier deepwater considered in this paper; however it is important to notice that offset control by using higher stiffness components needed to be traded-off for higher mooring loads and reduced fatigue life of the chain components, resulting in the need for larger mooring components, especially for highly dynamic floaters like FPSOs. Based on author's evaluations, designing a hybrid anchor leg system with a combination of polyester rope and high modulus synthetic rope (springs in series) should provide sufficient flexibility to the designer to come up with a combined stiffness between 18.5 times MBL to 55 times MBL, which would provide reasonable offsets while managing the dynamic responses.

Summary and Conclusions

The paper provides an overview of different stationkeeping strategies applicable to frontier deepwater regions with water depths up to 4,500 meters. The focus has been on stationkeeping technology used for FPSOs and the specific characteristics of these systems are identified. The main driver for stationkeeping performance is seen to be offset requirements of the riser system which tends to decrease (as a percentage of water depth) as the water depth increases. This offset requirement is shown to be a function of riser type which is also driven by water depth. In general, it is recommended to use an integrated design approach to the riser and stationkeeping systems to ensure the combined system is optimized.

The paper identifies disconnectable FPSOs as a solution for regions subject to hurricane environments as it can allow for the optimization of both the stationkeeping and riser systems with the trade-off of requiring a disconnectable turret mooring system. Currently the trend in the Gulf of Mexico is for FPSOs to be disconnectable. The paper also identifies that for frontier deep water dynamically positioned FPSOs may be an attractive alternative, especially for an extended well test or as an early production system with a short field life.

Taking advantage of lessons learnt from industry experiences with stationkeeping systems designed for deepwater and ultra-deep projects, recommendations are made for key factors in design of stationkeeping systems for frontier deepwater areas. Attention has been paid to the main design challenges regarding environmental conditions and soil properties, floater type, stationkeeping design philosophy, riser system, mooring system components, installation considerations, and regulatory environment.

The paper also discusses the use of high modulus synthetic fiber ropes as a component for the anchor leg systems. These high modulus ropes have a stiffness 3 to 4 times that of polyester rope and are shown to reduce the vessel offsets. A brief description of the most common high modulus fiber ropes with some relevant references has been provided. Though there are differences in the performance of the fibers for the purpose of this paper they are considered to be equivalent as the stiffness and weight of the various ropes are similar. It has also been identified that these ropes are currently 2 to 4 times the cost of an equivalent polyester rope and this is another parameter that would need to be considered as part of the design phase.

Using a case study, it is demonstrated that the use of higher modulus ropes results in higher dynamic extreme loads and higher fatigue damage than a mooring system with larger offsets made of polyester. This implies that the selection of the axial stiffness of the synthetic section of the anchor leg is important and that an optimum stiffness could be selected by using a combination of segments of polyester rope and high modulus synthetic rope, analogous to combining springs in series. It is expected that the use of these hybrid designs would be the most cost effective approach to optimizing the vessel offsets.

Acknowledgments

The authors would like to thank Cesar Del Vecchio (Stress Engineering Services), Mark Huntley and Chris Phillips (Whitehill), David Rowley (Offspring International), and Kosuke Ambe (Tokyo Ropes) for the information they have shared to support the development of this paper.

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