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FREE STANDING HYBRID RISER FOR 1800 M WATER DEPTH

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ABSTRACT

Petrobras is considering the single-line FSHR (Free Standing Hybrid Riser) design as an option for 18-in export risers in 1800 m water depth. This paper provides the background on the studies carried out to achieve confidence that the concept is feasible for such application, and explains the main features of the design that take best advantage of local practices and Petrobras capabilities.

The installation studies consider a Mobile Offshore Drilling Unit (MODU) for deployment of the FSHR system. The analyses assess the allowable sea states for such operation. Another design driver is the fatigue damage due to VIV (Vortex Induced Vibrations), which will also be addressed in the paper.

Model tests were performed in order to support the conclusions of the numerical analyses that established the operation window for the FSHR system deployment.

INTRODUCTION

The oil exportation of the P52 semi-submersible platform, located at Roncador field in 1800 meters water depth is planned to utilize a 18 inches OD FSHR (Free Standing Hybrid Riser). This alternative was developed through a FEED (Front End Engineering Design) contracted to 2H Offshore, according to technical specifications and functional requirements provided by Petrobras. Flow assurance studies require 50 mm thermal insulation material for the vertical portion of the riser.

The high expected production rates of the P52 platform require an 18 inches oil export pipeline. The instrumented pigging requirements dictate the export riser to have the same diameter. This large bore specification combined with the deep water site put this application outside the present feasibility range of solutions such as flexile pipes and steel catenary risers (SCRs). Both these solutions present high top tension loads for installation and operation. The lateral buckling failure mode in flexible pipes and the fatigue damage in the touch down zone (TDZ) of SCRs are further design limitations currently only solved by the use of heavier pipes which further compromise hangoff loads in a negative design spiral.

The FSHR system has a reduced dynamic response, as a result of significant motion decoupling between the Floating Production Unit (FPU) and the vertical portion of the FSHR system and its vessel interface loads are small when compared with SCRs or flexible pipe solutions. Therefore it is an attractive alternative solution for this kind of application. There are further cost savings associated with this concept due to the added advantage of having the riser in place prior to the installation of the FPU.

The hybrid riser concept, which combines rigid (steel) pipes with flexible pipes has been utilized by the offshore industry since the 80's. The Riser Tower first installed by Placid Oil [1] at Gulf of Mexico in Green Canyon 29 was refurbished and re-utilized by Enserch. More recently, the concept underwent some changes for application at Girassol field [2] in Angola, where three towers were installed by TFE. Other reference papers are [3], [4] and [5].

The Riser Towers at Girassol field are positioned with an offset with regard to the FPU, whereas at GC29 the vertical portion of the riser was installed by the FPU and was located underneath the derrick.

Petrobras has been studying the hybrid riser concept for some years. Five years ago this alternative was considered for conceptual studies at Albacora Leste field, in 1290 meters water depth, for the P50 turret moored FPSO. Two alternatives were considered for comparison: a Steel Lazy Wave Riser (SLWR) and one concept combining rigid and flexible pipes.

In 2003 Petrobras contracted the conceptual study development of the Riser Tower solution for the starboard side 8 inches production lines of the P52 semi-submersible platform.

Two towers were considered, each one comprising seven production lines and one spare line.

Five water and gas injection monobore FSHRs (10 to 12 inches) have recently been installed in West Africa offshore Angola, at Kizomba field in about 1200 meters water depth. The design of these risers has some key differences to the concept presented in this paper, each of which offers different design and operational advantages.

Two years ago Petrobras contracted 2H to provide the feasibility studies of an export oil FSHR to be utilized at P40. Due to changes in the in the field development planning, the study was further developed for the P51 and P52 semi-submersible platforms.

SYSTEM DESCRIPTION

The FSHR design may have a number of variants. The one described below is the base case considered for P52 oil export riser to be installed from a MODU due to the availability of such vessels already under contract at Campos Basin. The required design life is 25 years.

The FSHR consists of a single near vertical steel pipe connected to a foundation system at the mud line region. The riser is tensioned by means of a buoyancy can, which is mechanically connected to the top of the vertical pipe. The riser pipe passes through the central stem of the buoyancy can, which is located below the sea level, therefore beyond the zone of influence of wave and high current. A gooseneck assembly is located on top of the buoyancy can. A flexible jumper links the gooseneck to the FPU and significantly decouples the vertical part of the FSHR from the vessel motions.

The foundation may typically be offset from the FPU by more than 200 meters, depending on the optimization study, which takes into consideration the following parameters: (a) flexible jumper length, (b) riser base offset, (c) buoyancy can depth, (d) net upthrust provided by the buoyancy can and (e) the azimuth of the FSHR system.

Fig. 1 shows the FSHR General Arrangement.

The FSHR goes from the #1 hangoff slot at P52 to the Pipeline End Termination (PLET) located near the riser base. The lower end of the vertical part interfaces with a stress joint. Below the stress joint there is the offtake spool, which connects to the foundation by means of a hydraulic connector. A rigid base jumper connects the mandrels located at the offtake spool and PLET, providing the link between the FSHR and the pipeline. The foundation pile will be drilled and grouted.

The tension is given by the upthrust provided by the nitrogen filled buoyancy can located on top of the vertical pipe. The vertical pipe shall be kept always in tension in order to keep the FSHR stable for all the load cases.

The riser pipe passes through a inner 36 inches OD stem within the buoyancy can, and is guided within the stem by centralizers. Where the riser pipe is subject to high bending loads such as the keel ball centralizer on the buoyancy can, taper joints are used to reduce the stress in the riser pipe. The buoyancy can is secured to the riser pipe at the top of the can by means of a bolted connection.

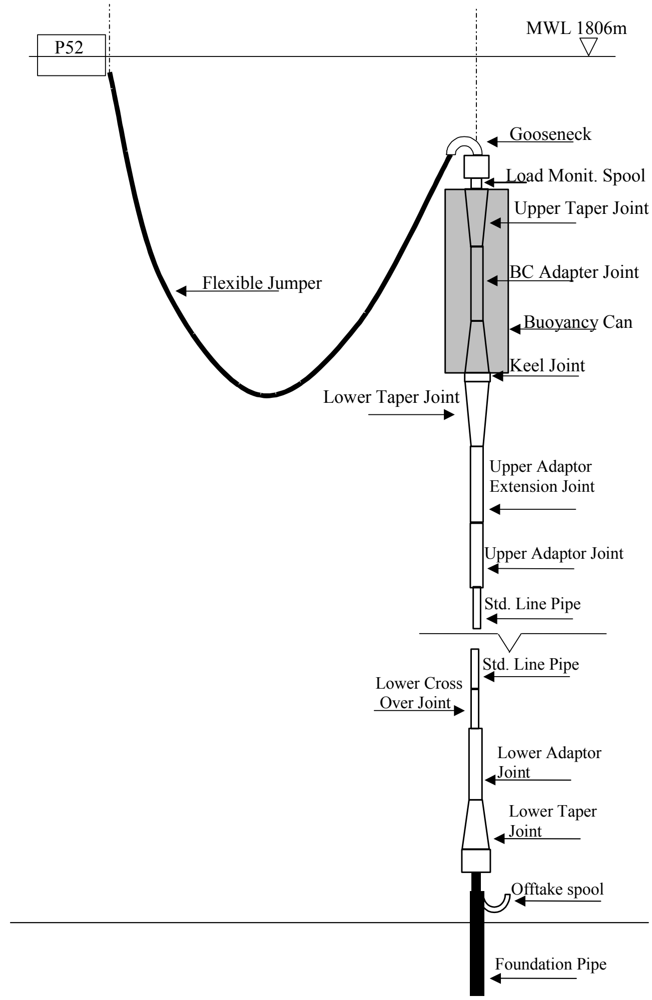

Figure 1 - General Arrangement

At the top of the free-standing riser is the gooseneck assembly. This assembly consists primarily of the gooseneck and an ROV actuated hydraulic connector which allows the gooseneck and flexible jumper to be installed separately from the vertical section of the riser. The gooseneck assembly also includes a cross-brace tied to a support spool in order to provide support against the loading applied to the gooseneck from the flexible jumper.

Attached to the gooseneck is the flexible jumper. The flexible jumper connects the freestanding section of the riser system to the vessel, and includes bend stiffeners to ensure that the range of rotations experienced at the end connections do not damage the jumper due to low radius of curvature. The flexible jumper has enough compliance such that the vessel motions and offsets are substantially decoupled from the vertical portion of the FSHR system, and consequently the wave-induced dynamic response of the free standing riser is low.

Differences from existing design

The position of the gooseneck in relation to the buoyancy can is the main difference between the West African and P52 FSHR designs. In the earlier design, the gooseneck is positioned below the buoyancy can and the vertical riser is tensioned by the can via a flexible linkage or chain.

This arrangement simplifies the interface between the buoyancy can and vertical riser, and allows pre-assembly of the flexible jumper to the gooseneck before deployment of the vertical riser. However, in the event of flexible jumper replacement or repair, an elaborate jumper disconnection system needs to be employed below the buoyancy can.

Positioning the gooseneck at the top of the buoyancy can allows for independent installation of vertical riser and flexible jumper. A flexible pipe installation vessel can install the flexible jumper at a time of convenience. This minimizes the risk of damage to the flexible jumper during installation as the procedure is similar to that of a shallow water flexible riser with the first end at the top of the buoyancy can. This design also facilitates and minimizes the time for flexible jumper retrieval in case of damage, in service, to any of its components such as stiffener, end-fittings or pipe outer sheath.

On the other hand, it is necessary to have a continual vertical riser string right through the centre of the buoyancy can to provide a connection hub for the flexible jumper at the top. This arrangement introduces interfaces between the riser string and buoyancy can which have to be carefully analyzed and engineered. In addition, installation analysis has also to be conducted to assess the loads on the riser string during deployment through the buoyancy can.

Other differences are the foundation type (suction piles x drilled and grouted pile) and bottom interface (flexjoint x tapered stress joint).

CHARACTERISTICS OF COMPONENTS

The main characteristics of the FSHR system are presented at table 1 below.

Table 1 - FSHR main characteristics

Foundation/FPU offset	360 m
Depth of buoyancy can	175 m
Length of flexible jumper	425 m
Flexible jumper azimuth (from N)	339.7^{o}
Base tension - in service (oil filled)	200 Te
Base tension - stand-by (water filled)	189 Te
Hang-off angle at FSHR side	40.2^{o}
Hang-off angle at FPU side	15.6^{o}
Leaning towards FPU, neutral condition	≈85m
FSHR angle w.r.t. vertical, neutral cond.	$\approx 3^{o}$
Oil mass density	841 kg/m^3
Pipe minimum radius of curvature	3D

The main characteristics of the buoyancy can are shown at table 2 below.

Table 2 - Characteristics of the buoyancy can

External diameter	5.5 m
Thickness	5/8 in
Total length	36.5 m
Central stem pipe	36x1 in
Number of compartments	16
No. of contingency compartments	1 or 2
Length of each compartment	2.143 m
Mass in air	205 ± 12 Te
Maximum upthrust	565 Te
In-service upthrust	514 Te

The vertical part of the FSHR is an assembly of standard joints and special joints, such as the stress joints at the bottom and top interfaces. The main characteristics of the standard joints are presented at table 3 below.

Table 3 - Characteristics of the standard joint

External diameter	18 in
Thickness	5/8 in
Material	X65
Thermal insulation thickness	50 mm PP
Density of insulation material	910 kg/m^3
Corrosion allowance	3 mm

The main characteristics of the flexible jumper are presented at table below.

Table 4 - Characteristics of flexible jumper

Weight in air, empty	305 kgf/m
Weight in water, empty	93 kgf/m
External diameter	0.5132 m
Internal diameter	16 in
Bending stiffness	133.41 kNm^2
Axial stiffness	750263 kN
Torsional stiffness	20505 kNm^2
Length of bending stifness	5.5 m

Components of the Lower Riser Assembly

The lower part of the FSHR is located above the foundation and consists of three components: the offtake spool, the lower taper joint and the lower adapter joint. The assembly interfaces with the seabed foundation at the bottom and the lower cross-over joint at the top.

Offtake spool

The offtake spool is a cylindrical component approximately 1.80m tall and 1.04m external, cast from 50ksi steel. The spool contains a flow path that travels through the top of the spool and exits from the side via an offtake. The offtake, formed as induction bend that exists from the side of the spool, presents an upward facing mandrel for connection of the rigid base jumper. A weld on compact flange connects the offtake to the side of the spool.

The offtake spool has a studded bottom for interface with the base connector and a studded top for interface with the lower taper joint.

Lower taper joint

The lower taper joint is forged component fabricated from 80ksi yield strength material. This is a high specification component designed to control the bending at the base of the riser.

It is a 10.4m long component with a linearly decreasing wall thickness and its profile is optimized to withstand both extreme loads and long term fatigue loading. The upper end is connected to the lower end of the lower adapter joint via a weld on compact flange connection.

Lower Adaptor Joint

The lower adapter joint is a 28.5m long section with 31.8mm wall thickness. The pipe is fabricated from a 65 ksi grade material, from two standard pipe sections welded together and a shorter pipe section to achieve the required length. Welded to the top is a seafastening collar which is used during transportation and installation.

Its function is to provide an interface and stiffness transition between the lower taper joint and the standard riser line pipe joints. Its length is such that it facilitates pre-assembly of the components to the buoyancy can for transportation offshore. Weld on compact flanges connections are utilized at its both extremities.

Riser line pipe

A special joint called lower cross-over joint is located just above the lower adapter joint and forms the connection between the lower riser assembly and the standard riser line pipe joints.

Lower cross-over joint

The lower cross-over joint consists of 12.2m joint of standard riser pipe with 15.9mm wall thickness. At the lower end there is a weld on compact flange. At the upper end of the joint is a handling collar with a weld profile above it to enable the joint to be welded to the standard riser line pipe.

Standard joints

The riser line pipe consists of approximately 58 double riser joints of 18inch outer diameter and 15.9mm wall thickness. It is specified as 65 ksi grade steel. Each double joint has a handling collar welded at the top of the joint to allow it to be handled using standard or adapted casing handling tools. The double joint length including the handling collar is 25.9m.

Bouyancy can taper joint assembly

At the top of the riser line pipe string is the buoyancy can taper joint assembly. The assembly consists of the upper adapter joint, upper adapter extension joint, buoyancy can lower taper joint, buoyancy can adapter joint and buoyancy can upper taper joint. This region is subjected to high bending moments due to the interaction of the riser with the buoyancy can, and thus a stiffened length is required to control the stresses during extreme and fatigue loads.

Upper Adaptor Joint

The upper adapter joint is as the transition between the standard riser line pipe and the thickened pipe used in the taper joint assembly. It consists of two joints of pipe fabricated from a 65ksi grade steel.

Upper Adaptor Extension Joint

The upper adapter extension joint is a 10.5m long forged component with an integral compact flange at the upper end, and a weld on compact flange at the lower end. The joint is located between the upper adapter joint and the buoyancy can lower taper joint, which is a critical location for both extreme stress and fatigue loading. It is fabricated from 80ksi yield strength material.

Buoyancy Can Lower Taper Joint

The buoyancy can lower taper joint is a forged component fabricated from a material with 80ksi yield strength. The joint is 10.8m in length and includes a double taper profile and a shoulder for the keel ball located at the centre of the joint. The taper profiles are both linear. At the centre of the joint is the keel ball. The keel ball interfaces with the buoyancy can central stem to provide centralization of the riser as it enters the bottom of the buoyancy can stem. The keel ball consists of a solid ring, which is located on the buoyancy can lower taper joint above the shoulder.

Buoyancy Can Adapter Joint

The buoyancy can adapter joint is located within the buoyancy can, and connects the buoyancy can lower taper joint to the buoyancy can upper taper joint. The adapter joint consists of two sections of special riser line pipe with 19" outer diameter and 31.8mm wall thickness, manufactured from a 65 ksi grade steel. Its length is 23.58m. Both ends of the joint are fitted with weld-on compact flange connections, which also act as the location point for centralisers for controlling the curvature of the riser within the extension of the buoyancy can. There are thus four contact points between the riser string with the buoyancy can stem: one at the top, two intermediate and one at the keel ball. The last three provide only horizontal restrain whereas the first cause the riser and buoyancy can to have the same linear and angular displacements in the three directions.

Buoyancy Can Upper Taper Joint

The buoyancy can upper taper joint is a forged component located at the top of the riser string, between the buoyancy can adapter joint and the gooseneck. The joint is fabricated from 80ksi yield strength steel and its length is 7.7m. At the top of the tapered section of the joint is a load shoulder with a flange profile, to which the load monitoring spool is bolted. The load monitoring spool in turn connects the load shoulder on the top of the buoyancy can. This provides the connection between the buoyancy can and the riser string.

At the top of the buoyancy can upper taper joint is a 16-3/4" 10ksi connector mandrel, to which the gooseneck connector is attached.

Load Monitoring Spool

The load monitoring spool (LMS) consists of a 1.1m long joint, with 38inch OD and 1inch wall thickness, fabricated from 65ksi grade line pipe. It has flange connections at both ends. The spool is located between the buoyancy can top and the buoyancy can upper taper joint. Its function is to transfer the upthrust generated by the buoyancy can into the riser string.

The spool will be fitted with load measuring sensors in order to monitor the integrity of the riser system. The monitored forces will be transmitted to the production platform.

The load path of the upthrust generated by the buoyancy can is shown in the Fig. 2 below. The upthrust is transmitted by the buoyancy can to the load monitoring spool base. The spool is compressed and transmits the load to a shoulder located at top of the buoyancy can upper taper joint. The load is then transmitted to the riser string, which will be in tension, providing then stability to the system.

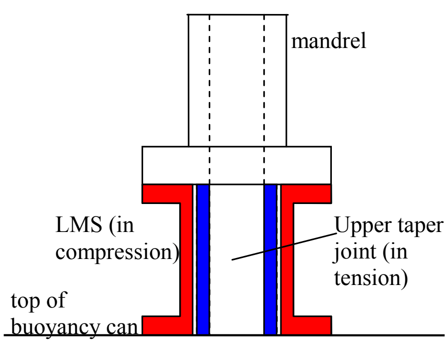

Figure 2 - Load path of the upthrust

Buoyancy Can Assembly

The vertical section of the riser system is tensioned utilizing a nitrogen filled buoyancy can. The can is a cylindrical design, 36.5m in length and 5.5m in diameter, fabricated from 50ksi yield material. It contains 16 compartments, each of 2.14m in height, separated by bulkheads. The buoyancy can is designed to be pressure balanced, with the internal pressure slightly above the external pressure of water. This approach resulted in the thickness of the buoyancy can to be 5/8inch.

Running along the longitudinal axis is a 36inch outer diameter central stem, with a 1inch wall thickness, through which the riser string passes.

At the bottom of the buoyancy can, a 2.25m long keel extension is fitted which consists of a continuation of the 36" stem pipe. The keel ball on the buoyancy can lower taper joint reacts against the keel extension, which is fitted with an oil impregnated bronze liner to reduce wear.

The buoyancy can is connected to the riser via a load shoulder located at the buoyancy can upper taper joint, to which the load monitoring spool is attached. The bottom of the load monitoring spool is positively connect to the top of the buoyancy can by bolts.

The buoyancy can is de-watered by means of ports located on the side of each compartment. Each compartment features an inlet and an outlet port. During de-watering nitrogen is injected into the can at pressure and the buoyancy can compartment is slightly overpressurized with regard to the water pressure outside.

The buoyancy can design is such that at least one of the 16 compartment is maintained permanently water filled as a contingency. Should one compartment fail in service, a contingency compartment can be de-watered in order to keep the operational tension in the riser string.

Fig. 3 shows schematically how the de-watering procedure is performed. The difference between the internal and external pressures corresponds to the length of each compartment.

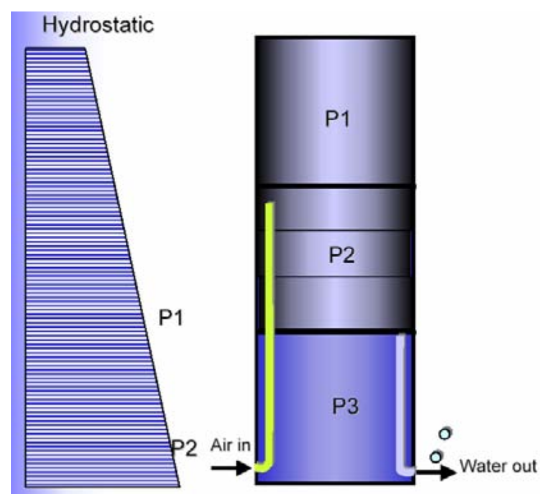

Figure 3 - De-watering procedure

Gooseneck assembly

The components located at the upper part of the system are described hereinafter.

Hydraulic Connector

A 16-3/4inch-10ksi hydraulic connector is utilized to attach the gooseneck to the riser string. The connector is hydraulically locked, and actuated via an ROV stab. The role of the connector is to allow the flexible jumper to be retrieved during service should the jumper be required to be fixed or replaced.

Gooseneck

At the top of the system is the gooseneck, which provides the change from the vertical section to the flexible jumper to the production platform. The gooseneck is a curved pipe, formed using induction bending with a 3D minimum bend radius. The lower end of the gooseneck is attached to the gooseneck support spool, which in turn is connected to the API flange on the connector.

Gooseneck support

The gooseneck is braced by a structural beam which connects between the upper end of the gooseneck and the gooseneck support spool at the lower end of the gooseneck. The support brace and support spool provide a load path for the loading applied to the riser from the flexible jumper, and prevent overstressing of the gooseneck.

Flexible Jumper Assembly

The flexible jumper assembly consists of the flexible jumper, end terminations and bend stiffeners at both the FSHR end and the production platform end of the jumper. A sketch of the flexible jumper assembly connected at the riser end is given in Fig. 4 below.

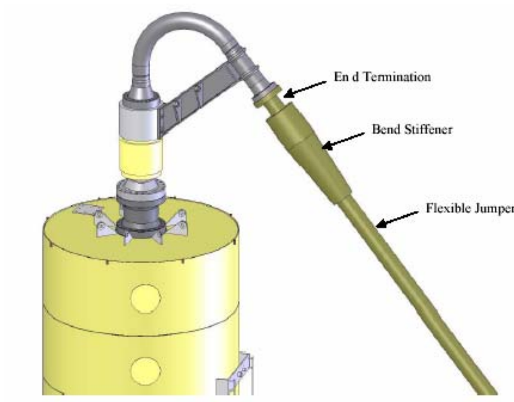

Figure 4 - Flexible Jumper Assembly

Flexible Jumper

The flexible jumper is a 16inch internal diameter, 425 meters long and rated for 3000 psi design pressure and 90^{o}C design temperature.

End Terminations

At both ends of the flexible jumper are end termination assemblies as specified by the flexible jumper manufacturer. At both ends of the jumper the termination is required to interface with a compact flange connection.

Bend Stiffeners

Bend stiffeners are located at both ends of the flexible jumper. Each stiffener is designed to meet the predicted range of jumper rotations at the both the gooseneck attachment and at the production platform connection. The bend stiffeners are designed and manufactured according to the details specified by the flexible jumper manufacturer.

INSTALLATION

The base case installation procedure is defined such that the FSHR can be installed using the P23 MODU. The procedure requires the buoyancy can to be transported to the work site separately from the riser, then positioned beneath the drilling rig. The riser is installed by continually joining and running the riser through the buoyancy can. Once fully assembled, the entire riser is then lowered to the seabed using drill collars and connected to the foundation. Some steps of the installation procedure is shown hereinafter.

Firstly some components of the lower part (hydraulic connector, offtake spool, lower taper joint and lower adaptor joint) are assembled to the buoyancy can, see Fig. 5 below. A sea-fastening collar is utilized for connecting the assembly to the top of buoyancy can.

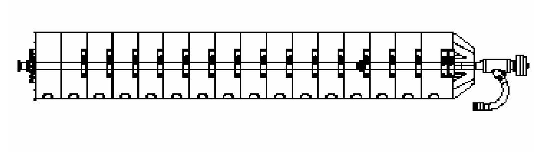

Figure 5 - Pre-installation of the lower riser assembly to the buoyancy can

Buoyancy can lifting onto barge

The buoyancy can is lifted from the yard by a crane and positioned onto the barge, see Fig. 6 below. After that a seafastening is provided in order to resist the barge motions during transportation to site.

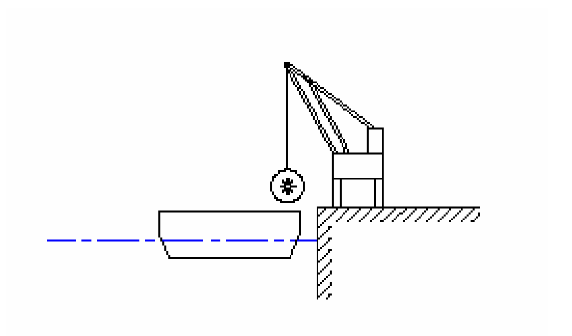

Figure 6 - Load-out of buoyancy can

Transportation of the buoyancy can

The buoyancy can and the pre-installed lower riser assembly within the buoyancy can stem are transported to the site of deployment.

Transfer of the buoyancy can to the water

At the proximities of the production platform, the buoyancy can and lower riser assembly are transferred from the transportation barge to the water, by a controlled flooding of the barge and sliding the buoyancy can, see Fig. 7 below. At this state, a wire rope connects the top of buoyancy can to the derrick of the MODU.

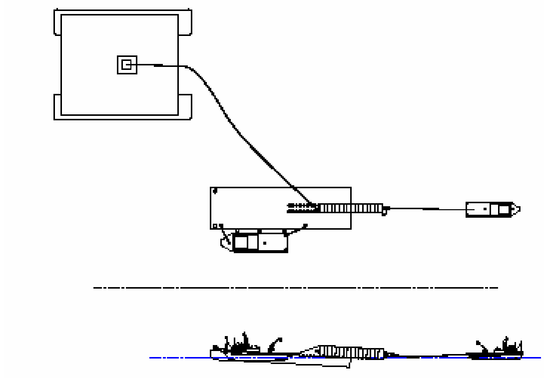

Figure 7 - Transfer of the buoyancy can to the water

Transfer of the buoyancy can to the MODU

After separation of the transportation barge, the uprighting of the buoyancy can is initiated, by means of a controlled flooding of some compartments. At this stage the buoyancy can has 4 compartments nitrogen filled, thus having overall negative buoyancy. The keel hauling process is then initiated, see Fig. 8 below, and the weight of the buoyancy can is transferred gradually to the derrick of the MODU.

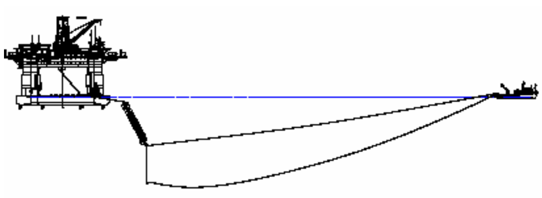

Figure 8 - Keel hauling of the buoyancy can

Buoyancy can beneath the MODU

At the end of the keel hauling process, the buoyancy can will be beneath the MODU derrick, still supported by the wire rope connected to the platform.

Buoyancy can supported by tensioners

After that the buoyancy can is lifted until its upper end is approximately 0.5m below the Lower Deck of the MODU and its weight is transferred from the keel hauling wire rope to the MODU drilling riser tensioning system, see Fig. 9 below.

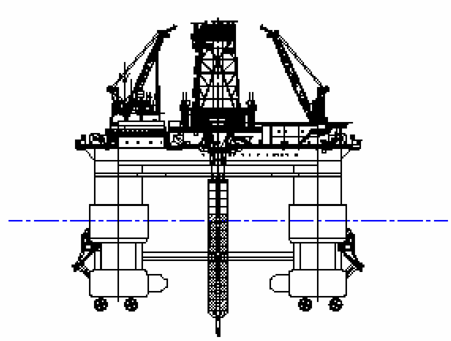

Figure 9 - Buoyancy can supported by drilling riser tensioners

Lowering of riser joints

The procedure for deploying the riser joints is shown hereinafter.

Lower Cross Over connection

The Lower Cross Over Joint is the first connection to be made to the pre-installed components of the FSHR system within the stem of the buoyancy can, see Fig. 10 below. After the connection is made, the seafastening collar at the top of the buoyancy can is removed.

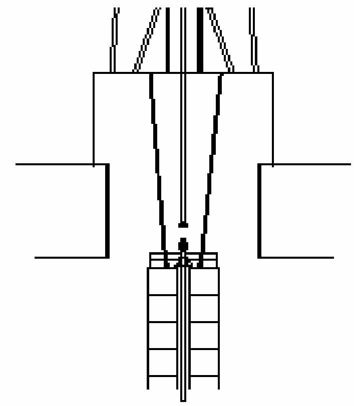

Figure 10 - Lower Cross Over connection to pre-installed components

Lowering of the Lower Cross Over Joint and first Standard joint

After the first connection aforementioned is made, the Lower Cross Over and the first Standard joints are deployed, such as the lower extremity of the string is approximately 40 meters below the buoyancy can lower end.

Lowering of the buoyancy can for deployment of the remaining joints

The buoyancy can is then lowered until its upper end is placed at the pontoon deck level, see Fig. 11 below. The buoyancy can is lowered by supporting the can on four padeyes on short chains, then transferring the load to the remaining four chains with longer chains using the full stroke range of the tensioners. Extension chains are then added to the 4 tensioners with shorter chains such that all eight tensioners are used. The buoyancy can upper end is connected by horizontal wire ropes to pulleys located in strong points at the pontoon level and to winches at the deck, such as to control the horizontal motions of the can.

The remaining standard riser joints are welded at the drill floor and run through the buoyancy can. The riser is allowed to water fill during deployment.

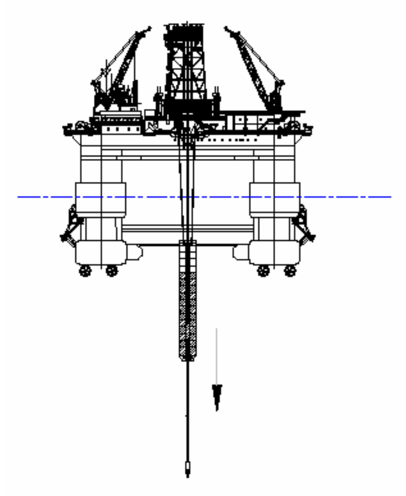

Figure 11 - Lowering of the buoyancy can

Lowering of the Buoyancy Can Upper Taper Joint to the top of the buoyancy can

Once all standard riser joints are welded together, the upper riser joints consisting of the upper adapter joint, the upper adapter extension joint, the buoyancy can lower taper joint, the buoyancy can adapter joint and the buoyancy can upper taper joint are run. These joints are made-up using flange connections. A riser running string is then attached to the connector mandrel profile at the top of the buoyancy can upper taper joint, and the riser string is lowered through the drill floor and lowered to the top of the buoyancy can, see Fig. 12 below.

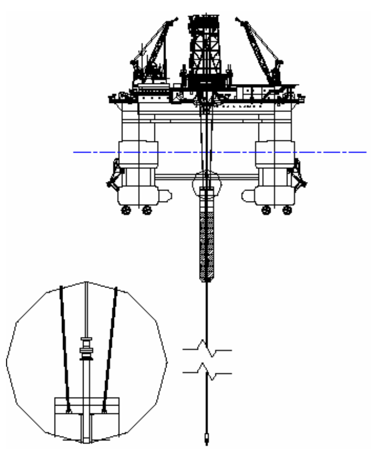

Figure 12 - Buoyancy Can Upper Taper Joint at the top of the buoyancy can

Raise of the buoyancy can and riser string

Both the buoyancy can and the riser string are then raised together to the level of the moonpool, where the riser string is landed on the top of the buoyancy can with a small landing weight. The flange connection between the load monitoring spool (attached to the upper taper joint), and the buoyancy can is made up, and thus a fixed connection between the riser and the buoyancy can is made, see Fig. 13 below.

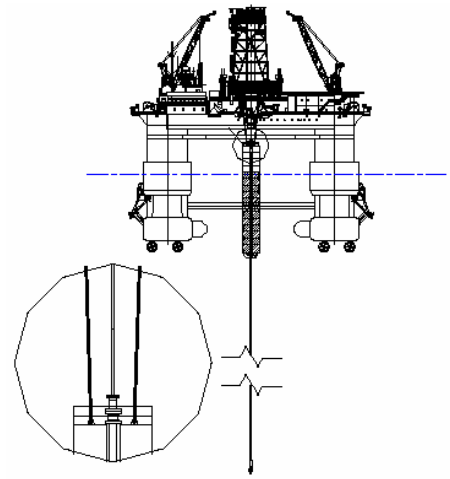

Figure 13 - Raise of the buoyancy can and riser string to the moonpool level

Lowering of the riser string and buoyancy can

The lateral restraint wire ropes are removed and the buoyancy can is released from the drilling riser tensioning system. The riser string and buoyancy can assembly is then lowered by using drill collars.

Riser string close to stab-in

During the lowering process, nitrogen is pumped under pressure into the top 4 compartments of the buoyancy can via a temporary manifold system to prevent them from filling with water. Prior to landing, a further 2 compartments are de-watered to reduce the net weight of the riser system to allow it to be landed using the motion compensator. Fig. 14 below shows the FSHR system in that configuration.

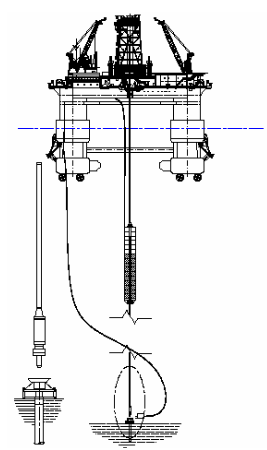

Figure 14 - FSHR near foundation

Riser landed on the foundation pile and locked down

The bottom of the riser is landed on the foundation pile, the orientation is set by a helix to ensure that the lower offtake is in correct alignment with the PLET, and the FSHR is locked down using an ROV.

After lock down of the hydraulic connector, it is necessary to tension the string by means of the drill collar, with two objectives: to test the hydraulic connector and to provide stability to the system, before initiating de-watering of the buoyancy can.

De-watering of the buoyancy can

After lock down of the hydraulic connector, the stability of the system is partly due to the tension applied by the drill collar string. The ROV starts the de-watering process of the buoyancy can compartments by means of injecting nitrogen. As long as the de-watering proceeds, the tension applied by the MODU is decreased, such as to keep the resulting tension approximately constant. At the end of the process, the tension provided by the buoyancy can allows the riser to free-stand and the drill collar string is disconnected from the top of the buoyancy can.

After conclusion of this process the flexible jumper is installed. The installation of the vertical section of the FSHR may take place before arrival of the production platform.

Installation of the flexible jumper

Connection of the gooseneck to the mandrel at riser top

The gooseneck attached to the flexible jumper end at the buoyancy can side is deployed by a Laying Support Vessel (LSV) and connected to the mandrel of the Buoyancy Can Upper Taper Joint. An ROV actuates a hydraulic connector, see Fig. 15 below.

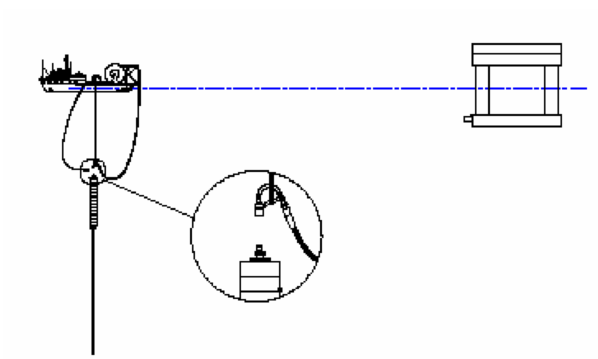

Figure 15 - Gooseneck connection

LSV installing the flexible jumper

The gooseneck and flexible jumper are first attached to the riser using the LSV, and the flexible jumper then un-reeled and pulled-in to the slot on the P52 platform, see Fig. 16 below.

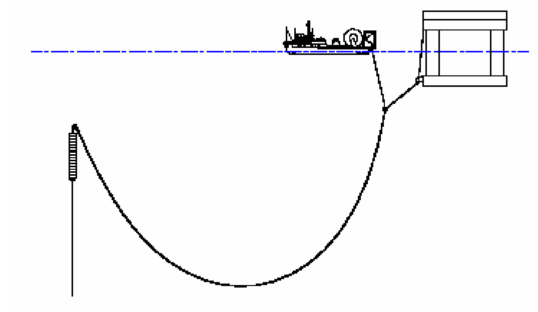

Figure 16 - Pull-in of the flexible jumper to P52

DESIGN APPROACH

The design of an FSHR typically involves an upfront global analysis of the system to optimize the riser configuration. Parameters to be varied are offset from the production platform, depth of buoyancy can, flexible jumper length and net upthrust provided by the buoyancy can. Clearance may be an issue and interference with adjacent risers or mooring lines drives the choice of the system layout. Following the selection of the system configuration, global storm and fatigue analyses are conducted to define the functional loadings on the critical riser components as well as Stress Concentration Factors (SCFs) requirements.

The FSHR comprises special components, such as taper joints, gooseneck, offtake spool and rigid base jumper, for which detailing will be required. In addition, the riser string components shall be able to withstand both the installation and in-place loads.

The FSHR benefits from the fact that the overall system design is robust and relatively insensitive to a number of parameters. Therefore, a relatively conservative design approach may be adopted for the upfront global riser design, with allowances for parameter sensitivities and design changes during design completion.

The system is designed and analyzed in accordance to API RP 2RD.

Riser Response and Design Drivers

Extreme Storm

As the riser and buoyancy can are located away from the wave zone and surface current region, the direct wave loading on the system is low. The flexible jumper connecting the vertical section of the riser to the production platform significantly decouples the riser motions from the vessel excursions and first order motions.

The riser response is driven largely by current and vessel offset, which causes an increase in loading in the gooseneck and also at the riser lower end. However this can be solved by local strengthening of the components. Another critical region is where the riser exits the base of the buoyancy can and a taper joint is required to withstand the interface loads.

At both ends of the flexible jumper, bend stiffeners are necessary to keep the curvatures in the flexible pipe within allowable limits.

Plots of typical bending moment distribution along the riser length under extreme storm shows two peaks, one at the riser base and the other at the interface with the base of the buoyancy can.

Along the majority of the riser string, the relationship between the combined Von Mises stress and the material yield strength shows a gradual linear increase towards the top of the riser, which is mainly due to axial tension and hoop stress in the pipe. At both ends of the riser however bending loads are present in the system, but are faced using special components such as taper joints, which control the curvature and stresses. Due to this, the stress ratios at the top assembly are lower than at the riser line pipe, in spite of higher effective tension and bending moments near the buoyancy can.

Along the vertical section of the FSHR, the stresses are practically static, barely affected by quasi-static loads (vessel static offsets and current) or dynamic loads (direct wave load and first and second order motions). The design of deeper components, such as the lower taper joint, is driven by quasi-static loads. The upper riser component designs are dictated by both quasi-static and dynamic loads.

Wave fatigue

The long term dynamic wave loading on the system is very low. The majority of the riser dynamic motion is associated with the second order drift motions of the vessel, which gradually alter the configuration of the flexible jumper and consequently the loading on the vertical section of the FSHR.

A typical plot of the wave fatigue life along the riser length shows that the damage is very low, however hot spots do occur at certain critical locations. These locations are at the lower taper joint, and at the bottom of the buoyancy can. Some precautions have to be taken in order to achieve the required damage limit at these locations, by sometimes refining the locally thickened joint designs. It is necessary that welds are either avoided or high quality welds are utilized, and that stress concentration factors are minimized in these regions.

Vortex Induced Vibrations (VIV)

The VIV response of an FSHR generates fatigue damage that is low along the majority of the riser length, but high at the two ends of the vertical section of the system. The critical region for VIV damage tends to occur in the riser string just below the buoyancy can interface. Shear7 was utilized for assessment of fatigue damage due to VIV.

It is necessary to design the components at the locations of peak fatigue damage such that they are capable of withstanding the predicted stress cycling. Generally, locally thickened components can be designed, or refined, to give adequate fatigue performance. The use of strakes is not necessary.

Installation and In-Place Fatigue of the FSHR system

The fatigue damage the system may undergo during installation shall be limited such as to leave most of the allowable damage to be spent when the riser is in-place. The installation analysis, mainly for the situation when the buoyancy can is at the moonpool region of the MODU, will assess the riser damage due to the MODU first order motions and from VIV.

Considering a safety factor of 10, the required system fatigue life is 250 years, which is fulfilled for the in-place condition. The in-place analyses have assessed the damage due to first and second order motions and due to VIV. The acceptance criterion establishes that the three sources of damage be added and that the resulting fatigue life be above 250 years. Most part of the damage is due to VIV, followed by first order motions. The damage due to second order motions is negligible.

ASSESSMENT OF VIV DAMAGE BY CFD

In addition to the assessment of fatigue damage due to VIV by using Shear7, the damage is being assessed by the utilization of the Computational Fluid Dynamics (CFD) methodology. Petrobras contracted the University of São Paulo to perform such studies. In this method, a finite element structural model based on the Euler-Bernoulli beam theory is employed to calculate the dynamic response of the cylinder. A general equation of motion is solved through a numerical integration scheme in the time domain. Firstly, a static solution is found for the riser. Then, in the dynamic analysis, the stiffness matrix obtained from the static analysis is used as an average approximation. A lumped approach is employed. A mass lumped matrix is constructed and the damping matrix is evaluated in a global manner.

The method utilized is the Discrete Vortex Method (DVM), which is a Lagrangian numerical scheme technique for simulating two-dimensional, incompressible and viscous fluid flow. The method employs the stream function-based boundary integral method and incorporates the growing core size or core spread method in order to model the diffusion of vorticity. In the DVM the body is discretized in N_w panels, and N_w discrete vortices with circulation Γ_i are created from a certain distance of the body, one for each panel. These vortices are convected and their velocities are assessed through the sum of the free stream velocity and the induced velocity from the other vortices. The induced velocities are calculated through the Biot-Savart law. Forces on the body are calculated integrating the pressures and viscous stresses. Viscous stresses are evaluated from the velocities in the near-wall region, and the pressure distribution is calculated relating the vorticity flux on the wall to the generation of circulation.

MODEL TEST

The installation phase is a critical issue for the design of the FSHR, mainly due to utilization of a MODU for deployment. The operating window is narrowed due to buoyancy can motions at the moonpool region, caused by the action of current and waves, and the resulting riser forces at the interfaces with both the buoyancy can bottom and rotary table.

Results from numerical analysis assessment show that the allowable sea states for some stages of the deployment are significantly milder when compared to the weather window of previous deployments of subsea hardware, such as manifolds, already performed by Petrobras utilizing MODU.

Modeling the entire FSHR system in 1800 m water depth would require a very small scale (approximately 1:180) and some important effects could be not well represented. Therefore it was decided to test the system behavior only during installation. A model test at the scale of 1:28.7 representing the buoyancy can, MODU and riser string was constructed and tested at Marin, see Fig. 17 below. The objective was to corroborate the results of numerical calculations.

Three phases were simulated: (a) buoyancy can free floating, (b) keel hauling of the buoyancy can and (c) buoyancy can at the moonpool region, suspended either by wire rope at the derrick or by the drilling riser tensioning system, and the riser string passing through the stem. Two riser lengths were considered: initial and total length. For the last, it was necessary to truncate the riser string.

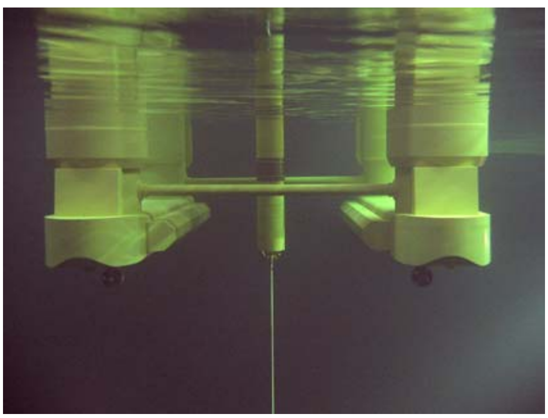

Figure 17 - Model test of installation at 1:28.7 scale

CONCLUSIONS

In the FSHR design concept, the location of the buoyancy can below high current and wave zone, and the use of the flexible jumper to significantly decouple vessel motions from the vertical riser greatly reduces the system dynamic response, resulting in a robust riser design particularly suited to deep water applications. The design is relatively insensitive to severe environmental loading and non-heave optimized host vessels when compared to SCRs and flexible risers. The robustness allows the riser to be conservatively analysed, and allowances for design changes and uncertainties to be included upfront in the design process, thus giving greater confidence in the overall system design.

For engineering, procurement and construction (EPC) contractors not having a suitable vessel, or unable to mobilize their vessels to install the FSHR, the ability to use a MODU as the installation vessel could prove to be an attractive alternative.

It can be said that the FSHR concept extends the reach of deep water riser feasibility as it avoids the main technical problems faced by the other solutions, and arguably, it may be the only proven riser concept feasible for deep water large bore applications.

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