

Design Challenges of Deepwater Dry Tree Riser Systems for Different Vessel Types

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ABSTRACT

This paper aims to review the key design features of a number of dry tree production riser systems, and to discuss and compare, by examples, the critical design areas in terms of extreme stress response, fatigue, and riser-riser clearance analysis. The paper also summarises the essential analytical techniques required to predict the dynamic behaviour of these riser systems.

KEY WORDS:

riser; deepwater; dry tree; production; buoyancy cans; top tensioned

INTRODUCTION

Dry tree production systems are continually being evaluated, selected and installed for deepwater developments worldwide. Each of these systems involves a floating host platform to facilitate tieback of the seabed wells, via top tensioned production risers, to a dry environment on the vessel where the pressure controlling Christmas trees are situated. Drilling and intervention facilities are selectively provided on the vessel to take advantage of the direct accessibility of the wells located below the production platform. This eliminates the need to mobilise specialist vessels for drilling and workover activities.

Different hull configurations have been used including tension leg platform (TLP) and Spar; and more are being proposed: barge, deep draught jack-up, etc. Each vessel has its own requirements for the design of the riser system because of the way risers can be supported and guided in the vessel; vessel motion characteristics; and riser tensioning and installation methods. The varied design requirements thus impose different loading conditions on the risers, leading to different critical load areas and riser component designs.

This paper presents an overview of key design features for three types of top tensioned production riser systems. The methods used to accurately predict riser response are also discussed and highlight the challenges of riser design. Results of global riser performance for each riser type are also presented focusing on critical design challenges for each riser type.

DRY TREE PRODUCTION VESSELS AND RISER SYSTEMS

General

Three generic dry tree production vessels and their respective riser systems are discussed:

- Tension Leg Platform (TLP)
- Spar
- Barge

The TLP is moored by its tendons, but the Spar and barge are usually spread moored by a taut mooring system to reduce the vessel excursions.

Because of the different hull forms, the motion characteristics of these vessels vary widely. Typical magnitudes and trends of their motions are illustrated in Figures 1 to 3 where head sea surge, pitch and heave RAO's are compared between the three vessel types.

All these vessels utilise top tensioned risers that tie back the subsea wells to the dry environment on the vessel deck where the Christmas trees are located. So as to accommodate the relative movements between the riser and the floating platform, flexible jumpers are used to connect the tree to the piping header on the deck.

The risers are installed directly from the drilling derrick on the platform by making up a series of riser joints equipped with threaded connectors. After connecting to the subsea wellhead on the seabed, the riser is tensioned by buoyancy cans or deck mounted tensioner systems.

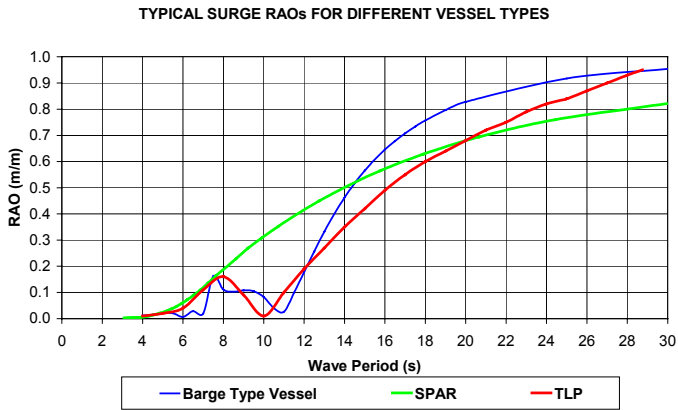


Figure 1 – Surge RAO Comparison for Head Seas

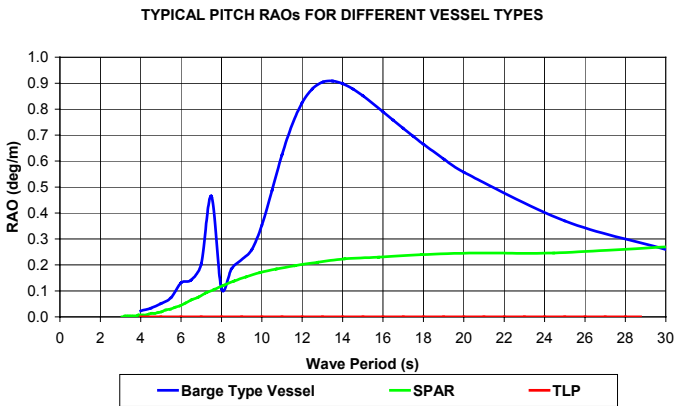


Figure 2 – Pitch RAO Comparison for Head Seas

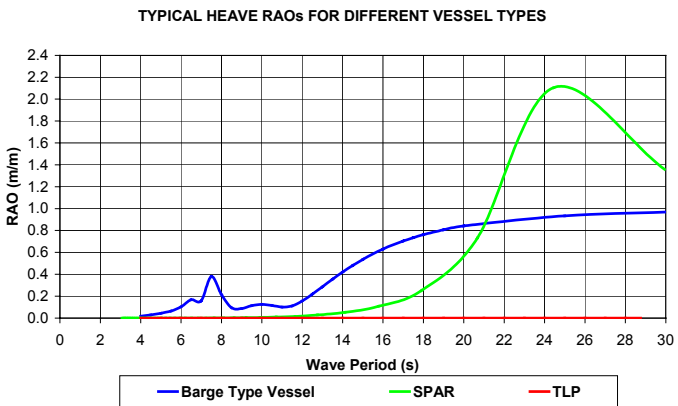


Figure 3 – Heave RAO Comparison for Head Seas

Tension Leg Platform (TLP)

The TLP was initially conceptualised for the harsh environment of the North Sea. The excess buoyancy of the ‘pulled-down’ hull, caused by the highly tensioned vertical tendons that anchor the platform to the seabed, suppresses vessel heave and pitch, Figures 2 and 3, and thus provides a stable platform for the production facilities. The only significant motions for the TLP are surge (and sway), Figure 1, and a

set-down phenomenon caused by the platform undergoing an arc-moion akin to an inverted pendulum.

The first TLP was installed in the Hutton field in 1984. Since then, there had been numerous other installations, both in the North Sea and Gulf of Mexico, and platforms are also being constructed for installation in deepwater fields offshore West Africa and Indonesia. TLPs have therefore been firmly established as a viable production facility in a wide range of environmental conditions and different geographical locations around the world.

The most common hull form for a TLP consists of four vertical columns linked by four horizontal pontoons forming a square at the keel level, Figure 4. Vertical tendons attached to the bottom of each column anchor the hull to the seabed. These columns and pontoons surround the wellbay that accommodates the top tensioned risers, but do not offer any effective shielding of the risers from the environment.

The risers are attached to, and individually tensioned by, hydro-pneumatic tensioner systems mounted on the platform deck, Figure 5. The riser strings usually span freely between the tensioner and the subsea wellheads they are attached to on the seabed and, as a result, are subjected to direct wave and current actions in the splash zone (Lim and Hatton, 1991).

The only riser/vessel interface occurs at the tensioner which normally incorporates a centraliser through which vessel surge motions are imparted to the riser.

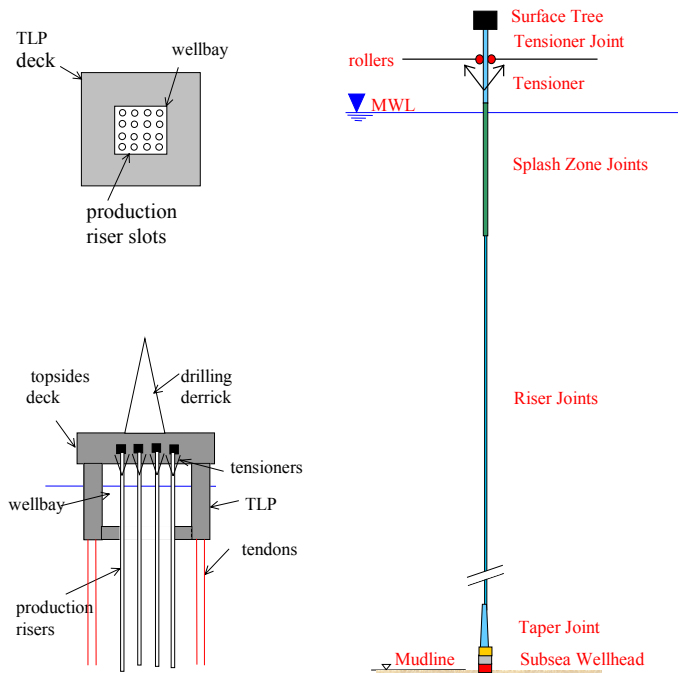


Figure 4 – Plan and Elevation Views of TLP and TLP Riser Arrangement

Spar

The Spar was first conceptualised for the Gulf of Mexico where the environment is characterised by hurricane and loop current events. The first Spar, in the ‘classic’ fully cylindrical deep draught hull form, was installed in 1996 in the Neptune Field. The deep draught enables it to respond with low heave and pitch when subjected to waves of periods normally encountered, Figures 2 and 3. The hollow in the cylindrical hull provides a passage through which the risers are routed to the deck where the surface trees are located.

The risers are of a free standing configuration, tensioned by buoyancy cans. With the exception of the first Spar, the buoyancy cans are non-integral to the riser and have an inner conduit for the riser to pass through concentrically, Figure 7. The upthrust provided by the buoyancy cans are transmitted to the riser as tension just below the surface wellhead via an upper stem. The buoyancy cans are shielded from direct environmental loading by the hull.

Together with their upper and lower extension stems, the steel buoyancy cans are guided (rigid or compliant) within the hull allowing relative vertical movement. The riser is centralised at suitable intervals within the buoyancy cans and exits the lower stem at the vessel keel elevation. This arrangement transfers the vessel surge and pitch (and roll) motions to the riser via the buoyancy can assembly.

The more recent Spar designs deviate from the ‘classic’ configuration in that the lower hull is a truss section. In this case, the buoyancy cans located in the upper hull are still shielded from direct environmental loading but the lower stem is exposed in the partially transparent lower truss section.

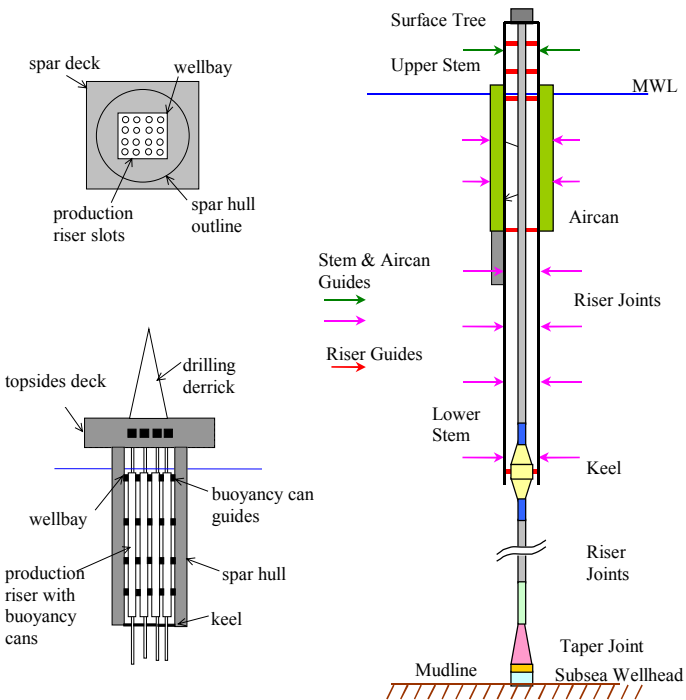


Figure 6 – Plan and Elevation Views of Spar and Spar Riser Arrangement

Barge

Barge type dry tree production vessels are suitable only for the more benign offshore environments, such as West Africa and Indonesia, as the barge motions would otherwise be too onerous for drilling availability and riser fatigue.

One such barge type vessel is the Wellhead Barge (WHB®) which has been developed by Saipem over the last 6 years with support from a number of major operators. 2H Offshore has been responsible for the design of the riser systems for this unique concept.

The WHB® has a large central wellbay, Figure 8, where the top tensioned risers are located. The motions of a barge compare unfavourably with a TLP or Spar, Figures 1-3, which is why it is only suitable for use as a dry tree production facility in locations where only small wave heights, H_s of 4-5m, are encountered (Stassen et al, 2001).

The production risers are of a free standing configuration, tensioned by buoyancy cans as for the Spar, but a key difference for these top tensioned risers is that on the WHB® they are only guided by the vessel at a single location within the wellbay. This arrangement ensures that interfaces and hull constraints between the barge and the riser are minimized as pitch and roll motions are not transferred to the riser. The relative vertical motion between the vessel and riser is accommodated as the guide allows the vessel to effectively move around the riser. Flexible jumpers connect the surface wellhead to the fixed manifold on the vessel.

There are two sections to the riser string, Figure 9. The upper string is located below, and directly tensioned by, the buoyancy can assembly. The remaining upper string is installed internally through a conduit in the buoyancy cans to complete the flow path to the surface tree.

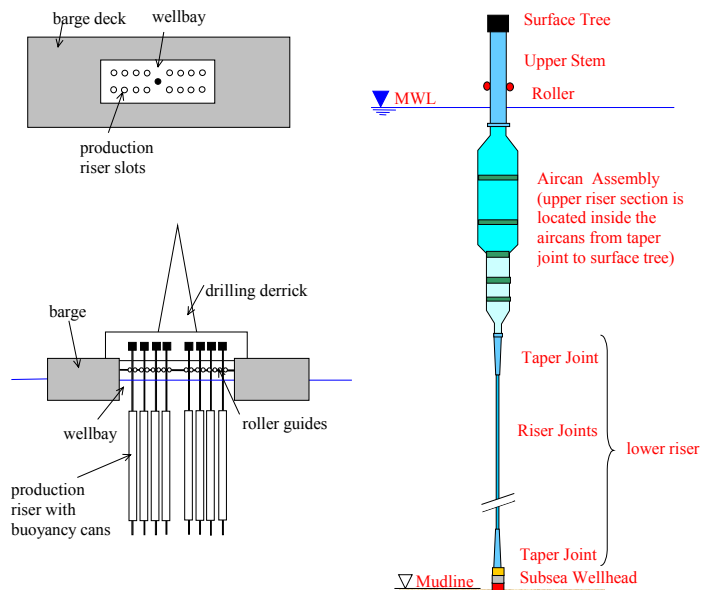


Figure 8 – Plan and Elevation Views of WHB® and WHB® Riser Arrangement

ANALYTICAL METHODOLOGY

Global riser analysis is carried out using non-linear time domain analysis programs such as FLEXCOM-3D. A suite of postprocessors developed by 2H is then used for assessment of riser response including riser stresses, riser displacements and fatigue.

Riser Modelling

Single-string and multi-string dry-tree risers are modelled using the same approach. The riser is modelled as a single string using pipe elements. Key properties of the pipe elements are determined by combining the properties of all tubulars in the riser system to form an equivalent single pipe riser. During post-processing, the output must be de-equivalenced so that the results can be determined for the casing of interest.

Typically a riser model will include part of the conductor system which is modelled to between 30 metres and 50 metres below the mudline. Soil strength data is required so that the conductor-soil interaction may be modelled in this region. Pressure-displacement curves are calculated along the conductor length in accordance with API codes [API-2A-WSD, 1993]. The soil resistance is modelled using non-linear springs, based on ultimate strength and ignoring cyclic effects. This ensures accurate prediction of riser response near the seabed, and also enables realistic subsea wellhead loads and motions to be predicted.

Extreme Storm Analysis

Extreme storm analysis is conducted using regular wave loading combined with associated currents. Regular wave analysis is conducted for at least five wave cycles with wave loading gradually ramped on over 20 seconds. Motion statistics are taken for the final two wave cycles when the riser dynamic response has stabilised. This is confirmed with response timetrace evaluation.

The load combinations include normal operating, extreme and survival conditions, in accordance with API codes [API-RP-2RD, 1998]. These are used to determine the riser stress responses and interface loads such as wellhead loads and moments and centraliser reaction loads.

Allowable stresses should not exceed the design criteria given in Table 1 below.

Table 1 – Riser Allowable Stresses

Load Category	Allowable Riser Von Mises Stress
Normal Operating	$0.67 \times \sigma_{\text{yield}}$
Extreme	$0.80 \times \sigma_{\text{yield}}$
Temporary	$0.90 \times \sigma_{\text{yield}}$
Survival	$1.00 \times \sigma_{\text{yield}}$

The definition of normal operating, extreme, temporary and survival load categories is given below:

Normal Operating

Normal operating conditions assume an intact riser working at the design pressure subjected to the maximum operating environmental loading (e.g. 1-yr or 10-yr event).

Extreme Conditions

Extreme conditions assume one of the following conditions while other parameters remain as normal operating:

- Extreme environmental condition (e.g. 100-yr event)
- Extreme pressure (e.g. shut-in pressure)
- damaged riser system (e.g. damaged mooring line, damaged tensioner / buoyancy compartment)

Temporary Conditions

Temporary conditions are those associated with installation/retrieval of the riser.

Survival Conditions

Survival conditions assume two of the following conditions while other parameters remain as normal operating:

- Extreme environmental condition (e.g. 100-yr event)
- Extreme pressure (e.g. shut-in pressure)
- Damaged riser system (e.g. damaged mooring line, damaged tensioner / buoyancy compartment)

First and Second Order Fatigue

First order vessel motions are those relatively short period (6-20 seconds) motions relating to the wave-induced motions of the vessel and are defined in terms of response amplitude operators (RAOs), see Figures 1-3. Second order vessel motions are generally long period (100-300 seconds) motions resulting from wind gusts and random sea loading.

First and second order fatigue analysis of risers may be carried out using a spectral fatigue analysis approach based on time domain random sea analyses of riser response or using the 'Rainflow' counting method. It is generally considered that 'Rainflow' counting provides a more accurate prediction of riser fatigue response although this is a more time-consuming technique. It may be prudent to employ the spectral fatigue analysis approach during early stages of a project in order to determine approximate riser fatigue performance prior to the full 'Rainflow' counting method which may be adopted after optimisation of the riser design. A brief description of both approaches is discussed below.

It is important to consider that the total riser fatigue damage is a summation of fatigue due to transportation/installation; first and second order fatigue; and VIV fatigue. The total fatigue life of the riser must exceed the design life with a factor of safety of 10 [DnV, 1984].

Spectral Method

The seastate scatter diagram is divided into a number of linearisation windows (e.g. 3 to 6). From each window, one representative seastate is selected for the purpose of response linearisation, and random sea analysis is carried out on each of the linearisation seastates.

Tensile and bending stress RAO's are calculated by Fourier integration of the riser response time trace for each linearisation seastate.

The fatigue damage resulting from each seastate is then determined using the total stress transfer function obtained from the appropriate linearisation seastate and assuming that stress peaks are Rayleigh distributed.

The damage from different seastates is summed using the Miner rule to determine the total fatigue damage of the system.

Rainflow Counting Method

Random sea analysis is conducted for all seastates in the scatter diagram. If the number of seastates is very high then they may be condensed into a smaller number of seastates (e.g. 15 to 30). Tensile and bending stress timetraces are extracted from the analysis.

Rainflow counting is then used to count the number of stress cycles in the timetraces and, therefore, the damage produced by each seastate.

The damage from all seastates are summed using the Miner rule to determine the total fatigue damage

VIV Fatigue Analysis

Vortex induced vibration (VIV) analysis is conducted using analysis software packages such as SHEAR7. These programs predict cross flow VIV response in sheared flow based on mode superposition. In addition, the natural frequencies and the associated mode shapes of each riser configuration may be determined using finite element programs such as ANSYS.

It is important to consider that the total riser fatigue damage is a summation of fatigue due to transportation/installation; first and second order fatigue; and VIV fatigue. The total fatigue life of the riser must exceed the design life with a factor of safety of 10 [DnV, 1984].

VIV fatigue should be determined for both storm events and long-term current events.

Storm VIV Fatigue

For storm VIV fatigue, a single storm current profile is considered and the fatigue life is determined assuming that this current profile occurs continuously. A storm event is typically a 3-hour event and therefore, the result of the storm VIV fatigue analysis is used to determine whether the riser will survive this one extreme event.

Long Term VIV Fatigue

Long Term VIV Fatigue - For long term VIV fatigue, current profiles of varying severity are assessed and the fatigue damage incurred due to VIV from each current profile is determined. The total fatigue damage due to VIV is then calculated from the sum of the factored damage for each profile.

Clearance Analysis

Clearance between adjacent risers is evaluated accounting for the effects of wake interference, wave effects and vortex-induced vibrations. This analysis leads to the determination of the minimum riser spacing required to prevent clashing in extreme conditions and the associated riser top tension.

In addition to riser/riser clearance issues, as discussed above, it is also necessary to consider potential riser/vessel interference. For all vessels discussed in this paper, space within the wellbay area is at a premium and, therefore, particular attention is given to minimising the overall space required by the riser systems. Potential interference between the risers and the vessel hull must be assessed as well as issues, such as jumper arrangements, which arise from the relative motion of the surface wellhead to the vessel.

TYPICAL RESULTS & DESIGN DRIVERS

Storm Response

The typical extreme storm response for the TLP, Spar and barge risers are illustrated as von-Mises stress distributions in Figure 10.

Common to all three types of riser is the peak stress region just above the subsea wellhead tie-back connection, as the wellhead fixity and riser movements both lead to high local bending moments. As the water depth becomes deeper, the dynamic bending stresses due to wave induced vessel motions in this region are less significant. This stress peak is thus due mainly to the quasi-static vessel horizontal excursion.

A lower taper joint, with a carefully chosen thickness profile and length, makes a smooth bending stiffness transition to the riser string directly above and helps relieve the bending stresses in this region.

For the TLP, the next peak stress region is in the splash zone where high dynamic bending stresses are caused by the direct wave actions. Thick walled joints may be necessary here to help alleviate the stresses. Another peak stress region is found in the tensioner joint, close to where it is guided by the deck centraliser, due to a combination of splash zone waves and horizontal movements of the Christmas tree. As a result, the tensioner joint has to be specially strengthened and profiled to maintain its structural integrity.

For the Spar, the next peak stress region in the riser is at the vessel keel where it enters the aircan stem. Here the vessel horizontal and rotational motions are directly transferred to the riser causing significant static and dynamic bending moments. A special keel joint is essential here to reduce the riser bending stresses to an acceptable level. The keel joint normally incorporates two back-to-back taper joints to provide bending stiffness transitions on either side of the contact point with the keel. As the buoyancy can assembly is non-integral to the riser, it is often analysed separately to address the dynamic sliding and bearing issues against the hull guides.

For the barge riser, the other peak stress region is at its interface with the buoyancy can assembly where there is a significant stiffness transition between the two components and the barge movements are transmitted to the riser via the buoyancy cans. A taper joint is essential here to ensure that bending stresses fall within the acceptable level. The buoyancy can assembly is considered as an important element in the riser dynamics, so is analysed as an integral part of the riser system. Extreme von-Mises stresses in the buoyancy cans and the upper stem are rarely an issue because of the large structural stiffness involved in these components.

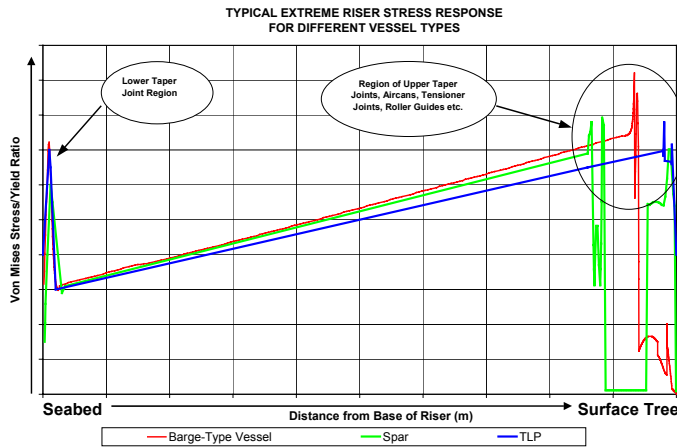


Figure 10 – Typical Plot of Extreme Riser Stress Response

Wave Induced Fatigue

Peak stress regions identified by storm analysis normally represent also the fatigue critical regions in a dynamic riser. However, as the extreme stress acceptance criteria do not account for fabrication methods and local geometrical details, what passes the strength checks may not meet the fatigue endurance requirements.

Riser fatigue performance is degraded by welding and high stress concentration. Welded riser components are avoided in regions of high dynamic stresses. If welding can not be avoided, then a high quality weld, such as double sided weld dressed flush complete with 100% Non-Destructive Examination (NDE), may need to be specified.

In the afore-mentioned high stress areas where special riser components are implemented: taper joint, tensioner joint, keel joint, etc, weld-free forgings, machined to the desired dimensions and details, are usually specified to maximise their fatigue lives. In addition, the components are carefully profiled to minimise stress concentration.

Special attention is given also to the riser joints adjacent to these special stress-relieving components. For example, immediately above the keel joint of the Spar riser, the riser is centralised within the buoyancy can stem. The centraliser locations are optimised to ensure that standard riser joints can be used without compromising their fatigue lives.

In the case of barge risers, dynamic stresses in the buoyancy can assembly may be relatively small, but the design of the buoyancy can assembly can be driven by bending fatigue considerations. As buoyancy cans are formed by seam and butt welding rolled plates together, consistent high weld quality is impractical to achieve so more conventional single sided welds have to be adopted. Together with stress concentrations arising from plate misalignments, the barge riser buoyancy cans become fatigue sensitive and require careful optimisation and detailing to minimise fatigue damage.

Spar buoyancy cans do not suffer much bending fatigue damage but, because of their multiple guiding requirements in the hull, can be susceptible to the 'stick-slip' frictional phenomenon that generate high dynamic axial stresses and thus fatigue damage in the riser.

TLP risers are not supported by buoyancy cans, but the hydro-pneumatic tensioner system exhibits linear stiffness characteristics that can generate dynamic axial stresses that add to the fatigue damage caused by bending stresses in the riser.

VIV Fatigue

Riser VIV fatigue is highly dependent on long term current speeds and profiles.

Spar risers are exposed to current loading only below the enclosed cylindrical section of the hull, so are not subjected to high current speeds that are generally found near the surface. However, the cylindrical hull can experience VIV itself, thereby imposing additional cyclic loading on the risers which has to be accounted for in the riser fatigue damage accumulation.

TLP risers extend through the splash zone, with little shielding from the hull, and so are subjected to the full current profile.

In the case of barge risers, the uppermost section of the riser is shielded from current by the hull. In addition, compared to the TLP risers, the extent and large diameters of the buoyancy cans significantly alter the modal characteristics of the riser system and lower the local vortex shedding frequencies.

Vortex suppression devices are fitted to the risers when it is found impractical to increase riser tension to reduce VIV.

Stroke

Calculation of potential maximum riser stroke relative to the platform deck is important for determining the deck headroom and, in the case of TLP risers, the tensioner stroke capacity.

Riser up-stroke and down-stroke are considered based on the following contributions:

- Thermal expansion
- End cap pressure effect
- Fabrication and installation tolerances
- Current
- Tide
- Wave induced platform heave
- Platform offset (and setdown for TLP only)
- Etc.

Whilst thermal expansion, pressure effect, tolerances and current affect the stroke nearly the same way for all three riser types, the effects of tide, waves and offset on the risers differ.

Rising tide increases the down-stroke for the Spar and barge risers, but not for TLP risers.

For Spar and barge risers, platform heave (coupled with pitch) contributes significantly to the riser up-stroke and down-stroke. It is not so for TLP risers.

Platform offset causes down-stroke for the Spar and barge risers, but up-stroke for the TLP risers due to the setdown effect.

In general, it can be said that TLP risers have a smaller relative stroke range compared to the Spar and barge risers.

Clearance

A major consideration during riser analysis is to assess potential riser/riser interference as the risers need to be accommodated within the limited space available in the wellbay.

Two identical risers are likely to respond similarly to the platform motions and environmental loading so they are likely to have nearly synchronised lateral displacements. Any clearance assessment must therefore focus on different riser sizes, internal fluids (e.g. production adjacent to gas injection) and scenarios (e.g. damaged riser).

Of the three production vessel types, Spar risers are the least prone to interference as they are separated only after they exit the deep draught Spar hull, and their horizontal displacements are governed only by the relative small Spar motions at the keel.

Given the same wells spacing and external environment, the barge risers are more susceptible to interference than the TLP risers because of the presence of the buoyancy cans. Wake interference effect is also more pronounced for the large diameter buoyancy cans on the barge risers. These shortcomings are, however, compensated by the fact that a barge has inherently much larger deck area which can afford a larger wellbay and hence well spacing.

Compared with the Spar and barge risers, interference between TLP risers are encouraged by their exposure to direct environmental loading in the splash zone, and it can be critical when the drive for cost savings has compelled the platform designers to minimise the deck size and, consequently, nominal riser spacing,

Consideration must also be given to assessing riser deflections during installation to ensure that there is no clashing with risers which are already installed (and may be producing), this drives the acceptable subsea wellhead spacing on the seabed. In this respect, the barge risers deflect the most during installation because the submerged buoyancy cans attract higher drag loading.

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