A HUB CLASS SPAR PRODUCTION PLATFORM FOR THE DEEPWATER NORTHERN NORTH SEA

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Abstract

The development of oil and gas reserves in the deepwater Northern North Sea will require innovative, low cost technical solutions. To meet this challenge Shell's hub class spar production platform design for the Gulf of Mexico has been adapted for service in the extreme Northern North Sea. The spar features an innovative hull design to minimize vortex-induced vibrations and associated drag enhancement in the strong prevailing currents, greatly benefiting the design of the mooring and riser systems. This paper summarizes the highlights of the concept feasibility study.

Introduction

The development of oil and gas reserves in the deepwater Northern North Sea will require innovative, low cost technical solutions. The oceanographic environment in this region is particularly harsh with frequent storms and deep, energetic currents associated with the Norwegian Atlantic Current and large scale basin circulations.

To meet this challenge Shell's hub class spar production platform design for the Gulf of Mexico (Mercier et al, 1998) has been adapted for service in the extreme Northern North Sea. The production platform has the flexibility to accommodate a large number of wells, both direct vertical access wells connected through top-tensioned, vertical risers and satellite subsea wells tied back with steel catenary risers. The spar features an innovative hull design to minimize vortex-induced vibrations and associated drag enhancement in the strong prevailing currents, greatly benefiting the design of the mooring and riser systems.

The spar concept is an attractive option for deepwater developments where direct vertical access is required as it is robust to changes in oceanographic environment and it scales easily with changes in payload and water depth. Deep draft spars with internal wellbays offer a number of advantages for riser deployment and avoidance of riser interference. But these advantages can be offset by the station keeping costs if there are requirements for vertical well access while under the influence of a strong current.

This paper summarizes the results of a study conducted to confirm the technical feasibility of Shell's hub class spar concept for deployment in the deepwater Northern North Sea.

Functional Requirements

The functional requirements used as the basis for the design of the hub class production platform are summarized in Table 1. The platform is designed to accommodate a very large number of steel catenary risers (SCRs) for subsea production from up to five satellite wells and from a total of eight import/export pipelines (four gas lines and four oil lines). Although the design is targeted for 700 m water depth, the feasibility of applying the design in the 600 m to 900 m water depth range was also investigated.

Table 1: Functional Requirements for Hub Class Platform

Water Depth	700	m
Nominal Topsides Payload	29,000	tonnes
CG of Topsides Payload	± 1.65	m
Direct Vertical Access	Yes	
Rig Capability	Full	(drilling & workover)
Dedicated Drill Slot	Yes	
Completion Tubing Size	4.5	inches
Peak Liquid Rate	19,000 – 32,000	m^3/day
Water Cut	25 - 41	%
Gas-Oil Ratio	90 – 360	m^3/m^3
No. of Production Riser Slots	16	
No. of Production SCRs	10	(2 per subsea tieback)
No. of Umbilical Pulltubes	10	(2 per subsea tieback)
No. of Export /Import SCRs	8	

Metocean Design Criteria

The deepwater Northern North Sea is here defined as the region beyond the 500 m isobath on the continental slope between the North Sea and the Norwegian Sea. As shown in Figure 1, this region is the location of a number of fields and prospects including Foinhaven, Schiehallion, and Clair in the UK sector and Ormen Lange, Helland Hansen, and Nyk High/Vema Dome in the Norwegian sector.

For purposes of defining design criteria, the following mechanisms must be considered as contributors to metocean conditions in the deepwater Northern North Sea:

1. local, wind-generated waves and surface currents from passing storms,
2. swell generated by distant storms,
3. the Norwegian Atlantic Current, and
4. deep bottom currents.

Maximum currents are associated with the Norwegian Atlantic Current flowing toward the northwest along the isobaths. The maximum current events are not correlated with storm events. The bottom currents are associated with very low frequency, large scale basin circulations which are amplified as they impinge on the continental slope.

Metocean criteria for the Norwegian sector of the Northern North Sea were developed based on an ongoing data gathering effort (Sætre, 1999). Table 2 lists the wind, wave, and current criteria for the 1, 100 and 10,000 year return periods. Note that the wind, wave, and current components listed at each return period individually correspond to that return period. For example, the 100-year wind speed is 38 m/s and the 100-year surface current is 1.7 m/s.

The combination of the 100-year wind speed, the 100-year wave height, and the 100-year current speed represents an event with a much longer return period, particularly since the extreme current events are not correlated with the wind and waves. Nevertheless, as this was a feasibility study and a limited amount of metocean data was available, the conservative approach of defining the 100-year design event as the combination of the 100-year values of the wind, wave, and current components was adopted.

Having said this, it must be noted from Table 2 that the rate of increase of intensity of the wind, wave and current components as a function of return period is not very strong. Consequently the "true" 100 year storm is probably not significantly less severe than that formed by combining the separate 100 year values of the wind, wave and current components.

Table 2: Representative Northern North Sea Metocean Design Criteria

	1-Year Return Period	100-Year Return Period	10,000-Year Return Period
Significant Wave Height (m)	12	17	19
Spectral Peak Wave Period (s)	16	18	19
Spectral Peakedness Parameter, γ	1.7	2.1	2.3
1 Hour Wind at 10 m Elev. (m/s)	31	38	40
Surface Current (m/s)	1.4	1.7	1.9
Bottom Current (m/s)	0.8	1.0	1.1

Spar Hull and Mooring Design

The general features of the hub class spar floating production system designed to satisfy the functional requirements and oceanographic criteria described above are illustrated in Figure 2. The spar supports a standard deck on the hull via a module support frame. The upper and middle hulls provide the buoyancy supporting the payload. The gap and the step discontinuity in the hulls provide mitigation of vortex-induced vibrations in strong currents. The lower hull is ballasted with high-density material to act as a counterweight and provide static rotational stability. The truss acts as the lever between the counterweight and the center of buoyancy.

The hulls are ring-stiffened plate structures with radial bulkheads from the wellbay to the outer shell. The main truss has four vertical members in a square arrangement. Diagonal bracing and horizontal framing between the vertical members provide the required strength in shear and bending. The horizontal framing, which is provided at three elevations, supports the guides for the risers.

In combination with the gap, the step discontinuity in the hull provides better vortex-induced vibration suppression performance than either the gap or step alone (this is discussed further below). For this reason the design concept is referred to as a step-gap spar.

As evident from Table 2, the storm seas in the Northern North Sea are extremely severe. To keep the vertical motions to a minimum, not only for human comfort but also to benefit the design of the mooring and risers, the heave natural period of the spar must be kept longer than about 30 seconds. The step feature in the hull allows this to be achieved in an efficient manner.

The mooring for the hub class spar is a 20-line chain-wire-chain system arranged in four groups of five lines. Each line has a single buoy. Due to the need to be able to perform riser deployment and well workover operations in the strong prevailing currents, the mooring system is actively controlled in the sense that it can be adjusted to control the mean offset of the spar. Each line has its own chain jack located on the top of the hull. Two separate control rooms and hydraulic power units are located on the lower deck on either side of the spar, each one operating ten mooring lines.

Mitigation of Spar Vortex Induced Vibrations

The Norwegian Atlantic Current is a predominant feature in the deepwater Northern North Sea. On the continental slope the current extends over the entire water column with little attenuation with depth. Average current speeds measured at the Helland-Hansen site, for example, are 0.2 to 0.3 m/s, ranging to maximum monthly values of 0.8 to 0.9 m/s. Exposure to this deep energetic current is a significant concern for the design of the mooring and risers as well as for drilling and riser deployment operations.

Spar platforms are particularly vulnerable to currents because they have deep drafts that attract more load. In strong currents, the frequency of vortex shedding from the spar may also overlap with the natural frequency of the sway and/or roll response and feed energy into these resonant response modes. Large amplitude vortex induced sway and roll vibrations will be set up which will cause the effective drag coefficient inline with the current to increase dramatically, thereby causing large tensions in the mooring system.

Based on the natural sway and roll periods of the spar and the relationship between current speed, hull diameter and vortex shedding frequency, it can be expected that the spar will undergo vortex-induced vibrations (VIV) when the current speed is in the range of 0.6 to 2 m/s. When the current speed is in this range transverse sway or roll mode VIV will lock in and the spar will oscillate at the natural frequency of the sway or roll mode.

Note that the VIV will not involve both sway and roll simultaneously. In a steady current without wind and waves the spar will lock onto one mode of VIV (sway or roll) and have a tendency to stay there. The more unsteady the current or the stronger the accompanying wind and waves, the greater the tendency of the VIV to be disrupted.

Under this condition the spar will intermittently lock onto one mode or the other for a while, with periods of no VIV in between.

To mitigate these vibrations special measures are taken to suppress the strength of the loads imparted by the vortex shedding process. The most commonly used technique is helical strakes (Figure 3). The sharp edge of the strakes controls the location at which vortex shedding will occur locally. Wrapping the edge around the platform ensures that the vortex shedding will not occur at the same azimuthal location along the full length of the spar, effectively reducing the strength of the transverse forcing. But since the strakes themselves add projected area to the spar, the reduction in the transverse forcing comes at the expense of increased forcing in the in-line direction. In addition, Figure 3 illustrates that strakes promote earlier flow separation and vortex shedding (relative to the incident flow) along much of the length of the hull, further increasing the in-line drag force.

The technique that Shell has devised to mitigate the effects of vortex shedding is to divide the upper hull into two sections and separate the two sections with a gap (Figure 3). The gap in the hull isolates the boundary layers in the top and bottom portions so that vortex shedding on the upper portion does not occur at the same time as on the lower portion. To further isolate the boundary layers on the two portions the diameter of the upper portion is reduced while that of the lower portion is increased by a commensurate amount to create a step discontinuity between the two portions. The flow around the step discontinuity experiences an end effect that produces the desired disruption to the boundary layer. This method of reducing the lateral forcing does not increase the in-line forcing. Another major advantage is that it doesn't require attaching special structures to the outside of the hull that could interfere with the hull fabrication and load-out or the attachment of appurtenances.

Without any kind of suppression device at all, the transverse excursions of the spar while undergoing VIV would be about 80% of the hull diameter. Extensive tests at very high Reynolds numbers have shown that the step-gap feature reduces the transverse sway VIV motion to about 25% of the hull diameter. In roll mode VIV the spar will rotate about a point near the keel with an amplitude of about 4°. By comparison, if instead of the step-gap feature the spar was designed with a constant diameter upper hull with strakes for VIV suppression, it is expected that the transverse sway VIV would be about 50% of the hull diameter while the roll mode VIV would be about 8°. In other words, the step-gap feature is twice as effective as strakes for mitigating VIV.

The superior performance of the step-gap design is also evident in the in-line drag that accompanies the VIV. Since the step-gap spar has lower VIV motions than that associated with a straked spar it follows that it must also have lower in-line drag enhancement, all else being equal. Coupled with the fact that the strakes actually add projected area to the spar and promote earlier flow separation, it should not be surprising that during VIV in a steady current a straked spar will experience substantially more in-line drag load than a step-gap spar. Indeed it is estimated that, in the 0.6 to 2.0 m/s current range when VIV sets in, the straked truss spar will experience 50% greater mean current load than the step-gap spar concept.

The step-gap feature is an elegant and efficient technique for mitigating the effects of vortex-induced vibrations in strong currents. It reduces the VIV motions and in-line drag enhancement to a level where VIV is really not an issue in the design of the mooring system. The VIV suppression provided by a straked spar is not sufficient to reduce the drag enhancement to this level. As the mean load imparted by the current is the dominant environmental component in the design of the mooring system the higher drag loads on the straked spar result in the need for additional mooring lines or larger line sizes. Consequently the cost of the mooring system for the straked spar is substantially greater than that for the step-gap spar.

Top Tensioned Risers

As illustrated in Figure 2, there is a rectangular well bay through the center of the hull that accommodates the top tensioned risers for the direct vertical access (DVA) wells. The risers are free to stroke vertically in the well bay but are restrained horizontally by a series of guides at various elevations. The production risers are arranged in a perimeter pattern with a dedicated slot for the drilling riser in the middle of the pattern.

The top tensioned production risers have a 13-5/8 inch diameter outer casing while the drilling riser has a 21 inch outer casing. For mitigation of vortex-induced vibrations strakes are installed on the production risers and fairings are installed on the drilling riser.

During riser deployment the mooring system must draw the spar back into the environment such that the mean position of the riser is nearly vertical over the wellhead. A guideline system is used to maintain adequate separation between the riser being deployed and those already installed and to assist with the landing of the riser on the wellhead. Analysis of a number of scenarios indicated that the weather downtime risk for deployment and landing of risers was acceptable.

Steel Catenary Risers

A number of different types of steel catenary risers were considered in the feasibility assessment including:

- 18 inch import/export oil or gas lines,
- 8 inch flowlines for the satellite wells either enclosed in a 12-inch carrier pipe (pipe-in-pipe configuration) or with 3 inches of external insulation, and
- a 28 inch gas export line.

The numerous steel catenary risers are hung off from baskets located at various points on the hull. In all cases helical strakes are installed over the top 600 m of the SCR for mitigation of vortex-induced vibrations (VIV).

The large number of SCRs has a significant impact on the mooring stiffness. As the SCRs are attached the tension in the mooring lines must be adjusted to compensate for the offset force. Analysis of the SCR performance under motions imposed by the hull indicated no problems with loss of tension, excessive top rotation angles, interference with the hull, over-stressing or fatigue. Indeed the analysis showed that the spar could accommodate a wide range of SCR design and installation options.

Motion Characteristics

The six modes of the spar motion are controlled in different ways by the wind, wave, and current components of the Northern North Sea environment.

The vertical heave motion is primarily in response to the waves with little sensitivity to the wind or current. The combination of deep draft and long natural heave period limits the maximum heave at the fairleads to less than 0.4 m in 4 m significant seas and less than 4 m in the 100 year return period 17 m significant waves. Vertical accelerations in the 100 year design storm are less than 2% of gravity.

The yaw motion is primarily in response to the wind and is strongly dependent on the heading relative to the deck and the layout of the deck itself.

The largest horizontal offsets occur when the wind, wave, and current components are colinear, in which case the mean offset is much greater than the dynamic component. As the mean load contributed by the current is the dominant component, anything that increases the drag characteristics of the spar will impact the cost of the mooring system.

While the deep currents of the Northern North Sea challenge the design of the mooring system their dominant contribution to the total horizontal load helps keep the hull inclination to a minimum. In the 100 year design storm the maximum hull inclination is about 7° if the wind, wave, and current components are colinear. The maximum inclination therefore occurs when the current is out of the picture, for example when the current is at right angle to the wind and waves or when there is essentially no current (other than the direct wind driven component). In such cases the maximum inclination can be as high as 11°.

The horizontal deck acceleration is primarily in response to the wave forcing with a secondary contribution from the wind. The horizontal acceleration is due to both the pitch and surge motions of the spar. Since the spar rotates about a point near the keel, the dynamic pitch component of the deck acceleration is quite significant.

In a frame of reference fixed to the spar, the maximum horizontal deck acceleration is about 35% of gravity in the 100 year design storm when there are no risers attached. The top tensioned risers have a substantial impact on reducing the dynamic pitch motions. Consequently with all risers attached the maximum deck acceleration in the 100 year design storm is about 15% of gravity, which is comparable to that experienced by TLPs and semisubmersibles.

Model Tests

A comprehensive model test program was conducted to validate the global performance of the hub class spar concept. The objectives of the program included validating the numerical models used in the design analysis of the spar and verifying that the design could accommodate the extreme mooring tensions, underdeck wave elevations, and hull inclinations experienced in the design storms.

A 1:70 scale model of the spar was built and tested at the Offshore Technology Research Center in College Station, Texas. The spar was instrumented to measure hull motions, tension in the mooring lines and top tensioned risers, riser stroke relative to the hull, water level fluctuations in the wellbay, and air gap. The spar was tested in the full range of Northern North Sea storm environments used as the basis for the design.

Although every effort was made to make the model tests an exact physical analog of the prototype, this was not possible for various practical reasons and some compromises had to be made. This is a common problem in model tests of deepwater structures. The compromises made include:

- inability to directly scale the mooring system because of the limited water depth in the tank, leading to use of an equivalent mooring system,
- inability to directly simulate the deep currents in the wave basin, necessitating use of an equivalent applied static offset force and resulting in neglect of the wave-current interaction contribution to the low frequency drift forces,
- scale effects in the drag loads on the spar, in the wellbay water level fluctuations, and in the modeling of the friction between the top tensioned risers and their guides.

The strategy employed to deal with these compromises was to incorporate them in the numerical model of the spar. For example, the drag coefficients assigned to the hull and truss were those applicable at model scale. The individual mooring lines and risers from the scale model were accurately reproduced in the numerical model, including their distributed weight, mass, and buoyancy properties. Every effort was made to numerically model the "as is" situation in the wave basin so that a true validation of the numerical model could be achieved.

Comparisons between the measured and numerically simulated frequency responses were quite good. The mean and rms spar offset and inclination and the tension in the most heavily loaded lines were generally predicted within 10% of the measurements. Figure 4 illustrates the comparison between the measured and simulated surge, heave, pitch, and mooring tension response spectra for the 100 year design storm event listed in Table 2.

The model tests also provided information on the extreme value statistics of the various responses and confirmed the excellent performance characteristics of the spar concept.

Conclusions

A comprehensive study has been performed to demonstrate the technical feasibility of Shell's step-gap spar concept as a hub class development option for the extreme Northern North Sea. The spar concept, which is based on Shell's Gulf of Mexico spar design (Mercier et al, 1998), has a number of features that make it particularly suitable for deployment in the deepwater Northern North Sea, including:

- a gap and a step change in diameter in the upper hull for effective mitigation of hull vortex-induced vibrations in the strong prevailing currents without accompanying increase in hull drag characteristics,
- an active mooring system in combination with a guideline system to enable deployment and landing of vertical risers in the harsh prevailing wave and current conditions, and
- accommodations for a large number of steel catenary risers for subsea tiebacks, and import/export pipelines.

An extensive analysis of the spar design was conducted to verify its performance in a range of operational and extreme storm seastates. To the extent possible the design was analyzed to verify compliance with Norwegian Petroleum Directorate standards. Numerical models were developed for the environmental loads, motion responses, and internal mooring and riser loads. These numerical models were subsequently validated in a model test program.

Several configurations of the steel catenary risers were analyzed including 18-inch oil and gas lines and a 28-inch gas export line. The analysis indicated that the spar could accommodate a wide range of SCR design and installation options.

The gap and step features in the hull greatly expand the flexibility of the spar to handle high current environments since this technique for mitigating vortex-induced vibrations of the hull results in very little increase in the effective drag area. This keeps the necessary increase in the capacity of the mooring system to a minimum.

The step-gap spar is a very promising concept that may be adapted to a range of field development options from hub for a large area to well control and production/export only for specific fields. To this end a system optimization capability has been developed to study the feasibility of alternative spar-based field development scenarios. Forthcoming studies will include assessing the techniques and the associated costs to fabricate and install spars in the Northern North Sea. The inclusion of hydrocarbon storage and subsequent offloading may also be the focus of future work. However, this spar concept is ready to compete with other deepwater systems in feasibility and concept selection studies for the Northern North Sea.

References

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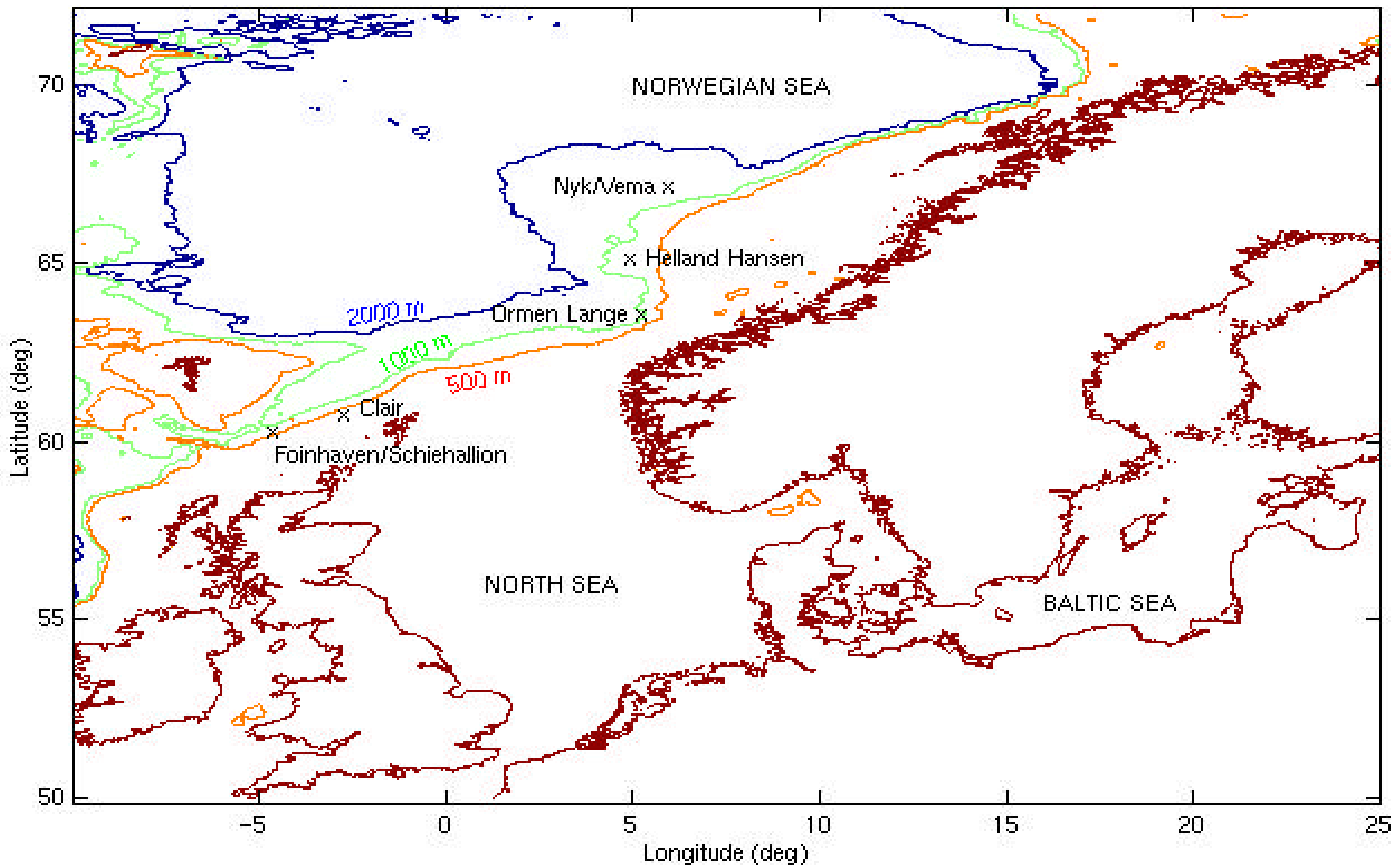

Figure 1: Bathymetry of Deepwater Northern North Sea

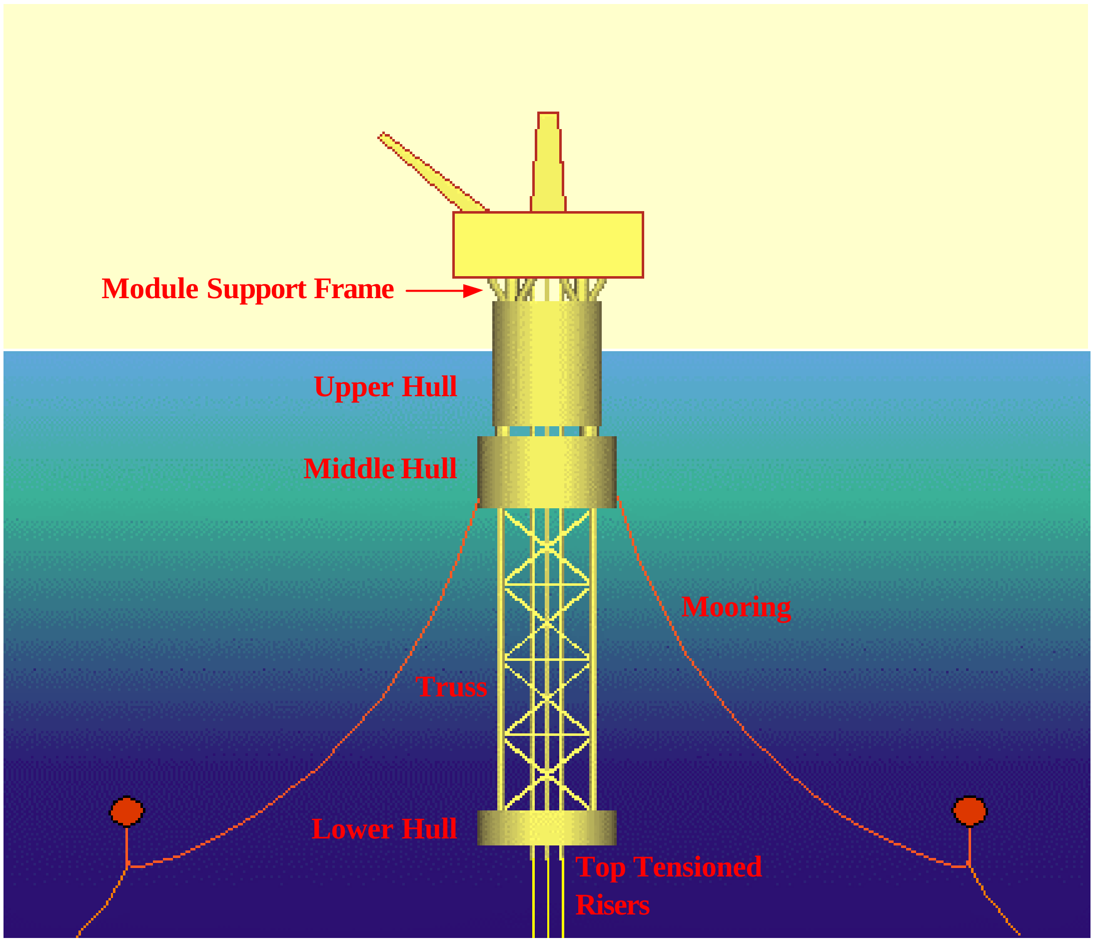

Figure 2: General Features of Hub Class Spar

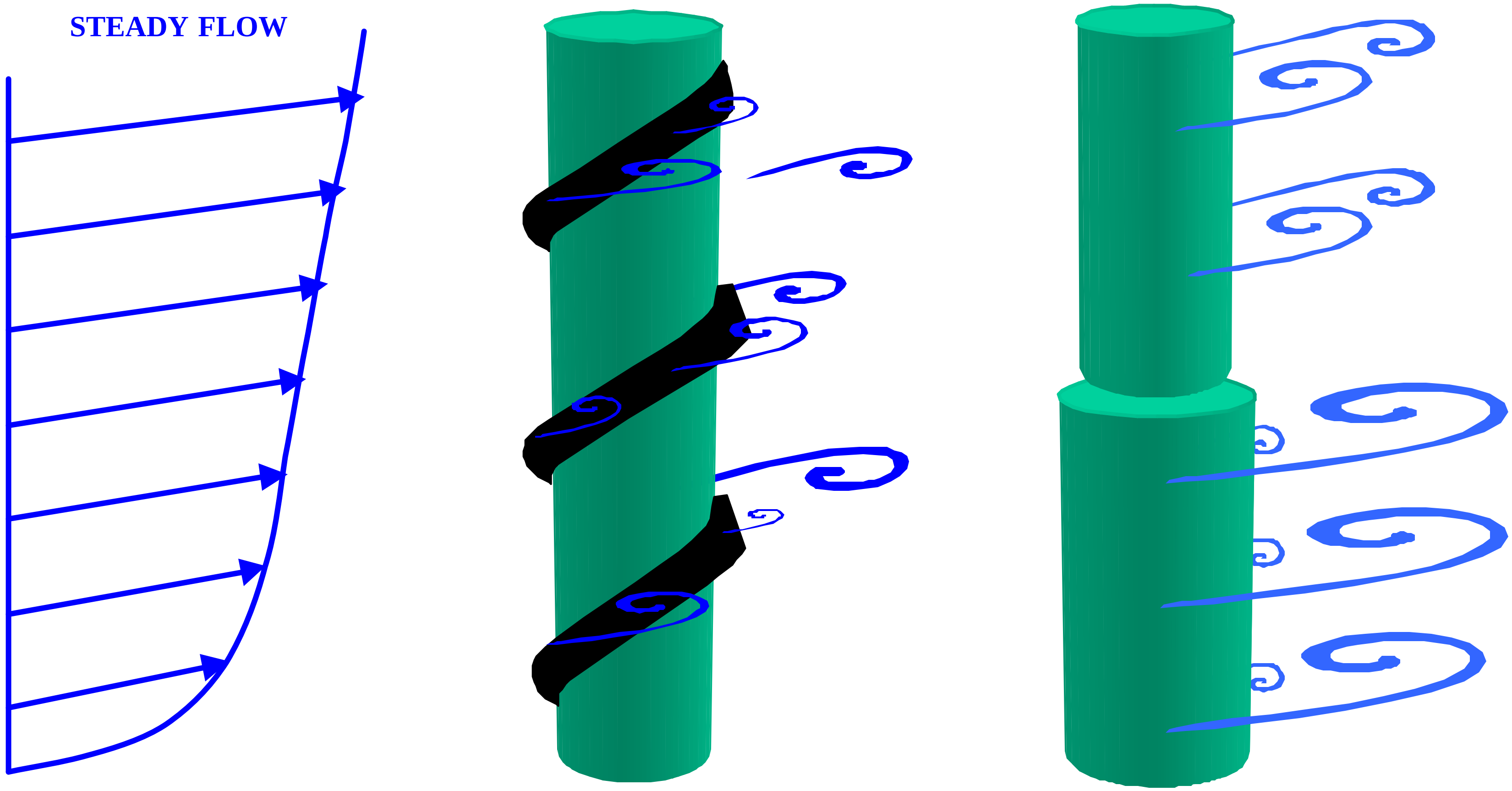

Figure 3: Vortex Shedding on a Straked Cylinder (left) and on a Cylinder with a Step-gap Discontinuity (right)

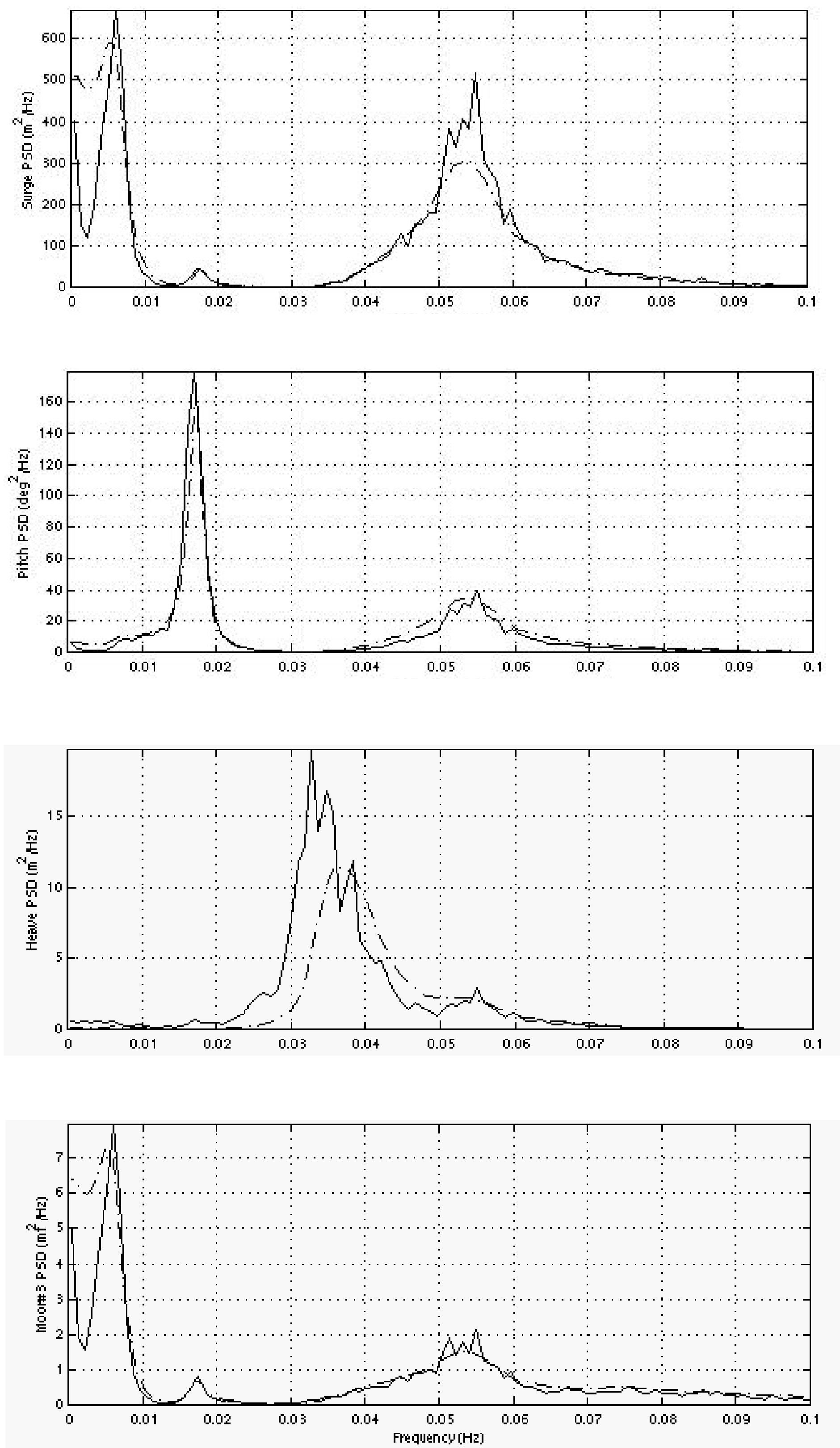

Figure 4: Comparison of Measured (solid line) and Numerically Simulated (dot-dashed line) Surge, Pitch, Heave and Mooring Tension Spectra for the 100 Year Design Storm