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Hydrodynamic and Structural Design Challenges in Benign Areas

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Abstract

The environmental conditions offshore West Africa are characterized as benign since the relative wave magnitude is significantly lower than found in other regions, such as the North Sea or Gulf of Mexico. However, there are certain unique design challenges encountered in this region that are caused by large period, persistent swells, squalls and high surface currents. As a consequence of the environmental characteristics, alternative field configurations may be considered, including spread moored FPSO's and multiple floaters connected with transfer and loading lines. The paper highlights some of the hydrodynamic and structural design challenges for these benign areas, typically:

- Use of spread mooring for a FPSO is a challenge with wind from squalls hitting the FPSO on the beam and resulting high tensions in the mooring lines/system.
- Mooring system installation challenges (e.g. duration for connecting the lines, unpredictable squalls, installation vessel dynamics).
- Swell sea is frequent and has a wavelength and direction producing persistent and relatively high bending moments/stresses in the hull structure and subsequent fatigue exposure on all FPSO components.
- Swell and wind generated sea in combination with asymmetry in topside masses induces roll motions/accelerations for an FPSO and may impact on the design of the risers/flowlines and topsides structures/equipment.
- Multiple floaters (typically FPSO, DTU and CALM) connected with flowlines and potentially hydrodynamic interactions may provide further challenges designing these field layouts.

The paper discusses the above issues and with generic examples show the importance of these typical hydrodynamic and structural design challenges Offshore West Africa (OWA).

Environmental Conditions

In order to show the level of benign environmental conditions OWA, a high level comparison of the main environmental parameters for the North Sea (NS), Gulf of Mexico (GoM), Brazil and OWA has been made. Refs /1/ and /2/ and other project specific data have been used to establish the comparisons of the environmental data.

Figure 1 shows a comparison of significant wave height (Hs) and wave spectral peak period (Tp). This is the approximate 100-year return period values (contour lines) and the differences in maximum significant wave heights for the different locations are clear. To be noted that only the swell component are included for the OWA data. These swell data should be representative for the area offshore Angola where the local wind generated sea is of less importance, typically T_p in the range 0 – 7 seconds and wave height (H_s) about 25% of the swell H_s. Also to be noted that for areas further north/northwest on the coast, e.g. offshore Nigeria, the ratio between swell and sea wave height is altered. This comparison shows the importance of the swell component with T_p > 20 seconds and swell H_s as high as 2.5 – 3m.

The yearly percentage occurrence for the different wave periods is of importance. This is visualized in Figure 2 and clearly shows the high percentage of high period swell waves for OWA. To be noted that the swell are included with 100% in the cumulative distributions. These data should be valid for the area offshore Angola. This figure also shows that there are a lot of waves near the vicinity of an FPSOs' roll resonance period (typically 15 – 20 seconds).

The combination of swell and wind driven waves OWA implies that dual-peaked wave spectra have to be incorporated in the design/analyses. This increases the analysis complexity, both with respect to software tools and expertise. Dual-peaked wave spectra have to be used in other parts of the world too, but not as dominating as for certain areas OWA.

Another important aspect with the environmental conditions OWA is the fact that the swell is usually approaching from a narrow sector, typically ± 20 – 30 degrees, which implies that a spread mooring can be applied with the bow/stern of the FPSO heading towards the swell.

Figure 3 shows a comparison of 100 year wind velocity (1 hour average and 5 sec gust/squall at 10 m above sea level) for the 4 considered locations. A special phenomena OWA are the squalls, which are high intensity wind gusts lasting for about one hour. These are difficult to forecast accurately and varies both in intensity and direction. The 5 sec squall level indicated (29 m/s) is also representative for the area offshore Angola. To be noted that offshore Nigeria, higher squall velocities (39m/s) may be applicable.

Current are usually very site specific making it difficult to perform a quick and consistent comparison. Generally speaking, the current OWA is not considered to be the most challenging load component for a spread moored FPSO located in deepwater. There is no loop current as present in GoM. There is, however, a relatively high surface current in the upper watercolumn. This high surface current is thought to be caused by wind driven water from the main rivers and may generate current speeds in the range 1.7 – 2 m/s in the upper few meters. Another phenomena is the so-called jets which can occur at different waterlevels with a triangular shape and vertical range of some few hundred meters. The peak intensity of these jets is usually in the range of 0.4 – 0.6 m/s at the 100 year recurrence level.

Design and Characteristics of a Typical Spread-Mooring System

Mooring systems for spread-moored FPSOs OWA typically are designed as grouped mooring systems with fairleads at the corners of the vessel. Typically the number of anchor legs range from twelve (12) to sixteen (16) with three or four anchor legs in each group, approximately 5 degrees apart. The anchor legs typically have a taut or semi-taut configuration and constructed with chain and spiral strand wire or polyester rope. The mooring system is anchored using suction embedded piles or vertically loaded anchors. Fairleads are located either at the vessel keel or at the main deck. For water depths greater than 1,000 meters the fairlead to anchor horizontal distance is typically 1.0 - 1.3 times the water depth. Typical maximum vessel offsets for an intact mooring system are 5% of water depth. Figure 4 provides an example of a typical spread-moored system for OWA.

As for all FPSO systems the primary goal in the design of the anchor legs is to safely moor the vessel and provide suitable stationkeeping for the various riser systems in all environmental conditions. However, the large FPSOs designed for OWA have some characteristics that have made the design of these mooring systems fairly unique. One major reason for this is the use of a deepwater offloading buoy and connecting Oil Offloading Lines (OOLs) that typically depart from one end of the FPSO. Due to the weight and length of these OOLs, each OOL exerts a force on the FPSO that is equivalent to that of an anchor leg. In addition the large FPSOs may have a large number of risers attached to the vessel that also exert large forces on the vessel. Summing up the external forces from the OOLs and risers results in large surge and sway forces, and a yaw moment that have to be counteracted by the mooring system in addition to the environmental loads to maintain the vessel at the desired heading and position.

The asymmetry of the external forces caused by risers and the OOLs attached to one end of the vessel result in the design of an asymmetric mooring system. The mooring asymmetry may either be accomplished by varying the number of anchor legs in a group and/or varying the pre-tension and anchor leg length. One characteristic of such a mooring is that the stiffness is also asymmetric and thus for a given load, vessel offset will vary as a function of direction. The mooring system is typically "softest" when offset away from the offloading buoy as the force from the OOLs is fairly constant with offset. Another unusual characteristic of such an FPSO mooring system is that the static equilibrium position of the FPSO may vary by 10 meters with change in draft from ballast to fully loaded. Figure 5 provides some typical mooring system restoring curves for surge, sway offsets and yaw rotations. For this particular example the OOLs are attached to the port-bow of the vessel and the impact on mooring stiffness can be observed.

As described in an earlier section of the paper, the environment OWA can be characterized by persistent long-period swells from the SSW with uncorrelated low-intensity wind and current environments. The OWA environment is also characterized by squalls that are of short duration (typically one hour) and very high wind speeds (5 sec gust greater than 30m/s). Squalls typically originate over land and propagate over the ocean, but locally can be incident from almost any direction. These high wind speeds coupled with the very large FPSO systems results in large vessel offsets and thus anchor leg tensions, and typically govern the design of the mooring system from an extreme load and offset perspective. As the vessel is typically oriented with its bow, or stern towards the SSW the loading from the swell on the FPSO is minimized but due to its persistence results in defining the fatigue life of the mooring system. Thus the wind squalls and the swell environments are important for analyzing and designing the mooring system.

A typical mooring system analysis and design effort uses design load cases created for (a) the extreme wave environment (swells) and associated environment, (b) extreme wind environment (squalls) and associated wave and current and (c) extreme current environment and associated wind and waves. In addition, a detailed description of the combined wind, wave and current environments are developed to perform a fatigue analysis of the mooring system components and the associated offsets for riser design. For the extreme loads the cases (a) and (b) usually provide the governing cases. The extreme current environment is typically more important in riser design.

As the swells are incident from a very small sector of approximately 45 degrees centered about the SSW direction, large offsets occur towards the NNE with high tensions and fatigue damage on the groups of legs oriented towards the SE and SW. For the extreme swell conditions (say 100-year event) it is recommended to perform the mooring analysis to provide extreme loads for a duration of 12-hours, compared to the typical 3-hour duration maxima estimates used for other locations in the world. Other than the duration of the extreme seastates the global analysis of the system is performed similar to those in other regions.

Figure 6 presents results of FPSO midship offset from an analysis performed with a generic FPSO in 1000 meters of water for the extreme swell environment. It is seen that the maximum offsets in the swell environment are fairly localized in direction and as the vessel heading is into the swell, the yaw response of the vessel is minimized. It is also seen that offsets for this system are on the order of 3% of water depth.

Analysis of the mooring system for squall environments is not common for other regions of the world. The analysis is complicated as the squalls are transient phenomena and in most areas there is insufficient data to allow accurate prediction of extreme wind velocities and their distribution in time and space. As squalls are very local events there is a lot of debate on what correlation length should be assumed for the maximum wind speed when performing the global analysis of a large body like an FPSO. At the current time there are no industry standard methodologies for defining and modeling squalls for a global analysis, and thus there is the possibility of a large uncertainty in estimating the extreme responses of the FPSO. This is even more critical in the cases where the design of the mooring system is governed by the squall environment. It is recommended that when possible, wind tunnel tests be conducted to derive accurate wind load coefficients for the FPSO to reduce the uncertainty of the maximum loads and offsets.

One approach that has been used by the authors in analyzing FPSO systems in squall environments is outlined below, and some typical results of vessel offset are provided. One approach in defining the squall environment is to take time histories of measured squalls (from any site Offshore West Africa) and scale the velocities to result in a peak velocity that equals the estimated extreme squall wind speed (1-minute wind speed for FPSOs) at the desired location. If one has a large enough number of independent squall time histories this allows one to build a series of realizations of the squalls for the desired location. A time domain analysis of the FPSO system is performed using the squall time histories as input and the responses of the system estimates for a number of incident directions. A most probable maximum response (offset, tension) can then be estimated based on the estimated squall duration and number of realizations generated. This method, though time consuming, is considered the best available to capture the transient response of the FPSO to the squall environment. Some issues that could be raised with the method is that (a) is the scaling of the squall velocities using an existing time series without modifying the time scale physically correct? and (b) scaling the realizations to have the same maximum value inherently assumes that there is no extreme value distribution of wind speeds. It is hoped that as more data collected and analyzed that the quality of the input data can be refined.

Figure 7 presents the results from an analysis performed with scaled time histories of the squall environment for the same generic FPSO described above incident from the North. For this particular example 7 time histories that vary in time and direction (about a mean value) were used. The vessel response (midships offset) is described by the lines in various colors. It is seen that the response for each of the 7 squall time histories is fairly unique. Figure 8 presents the results from running one squall from the NW to the South (via East) in 22.5 degree increments. The figure shows that the offsets vary as a function of direction with the largest towards the SSE that is close to 5% of water depth. These large offsets are due to the softness of the mooring system (OOLs depart towards NW) and the large wind loads on the system, especially when incident beam-on to the FPSO. Figure 9 presents an extreme offset envelope for the 100-year squall environment obtained by averaging the peak values from the individual squall time histories.

A very important interface for the system engineering is the interface between mooring and riser engineering. This is especially true for large spread-moored FPSOs with a large number of risers distributed along the length of the vessel. Due to the yaw motions of the spread-moored vessel (especially in squall environments) the design offsets of the vessel may vary by 50% depending on whether it is attached near midships or near the bow/stern. This requires the mooring and riser designers to work closely in the design phase to ensure that consistent environmental conditions and vessel response data is used to design the riser system. This is especially true for systems with a large number of risers as conservative assumptions can lead to interference between risers, or insufficient space to locate desired number of risers.

As the ratio of the extreme seastates to the 95% occurrence seastate is not very large compared to most other regions in the world, the design of many FPSO components can be governed by fatigue loading. This is especially true for the chain and connectors due to their relatively low fatigue life compared to spiral strand wire or polyester, and is a very important design consideration. This is especially true at the fairleads of the FPSO as the mooring chain may be subjected to additional stresses that are not directly obtained from a global/mooring analysis due to the interaction with the fairlead. The fairleads may result in a fatigue life reduction factor of 90% compared to the segments in pure tension and it is recommended that the interaction of the mooring leg with the fairlead be studied in great detail to develop accurate stress estimates. In many cases it is necessary to increase the size of the chain at the fairlead to provide the desired fatigue life.

Spread-mooring installation challenges

Installation of deepwater mooring systems presents numerous technical challenges both in terms of installing the individual anchor legs and in hooking up the vessel. This is further complicated in West Africa due to the presence of persistent swell and the unpredictable nature and intensity of West African squalls.

Unlike other regions of the world where there exist periods where the seas are relatively calm due to the small wave heights and short wave periods, the long period swell results in the installation vessels undergoing relatively large heave and pitch motions that results in increased dynamics during lifting and lowering operations. Most permanent mooring systems in West Africa are anchored using suction piles that may weight 150 – 175 MT. During the lowering operation a vessel heave of 1 meter amplitude can result in the suction pile heaving +/- 4 meters due to the dynamics in the system with large velocities – greater than 1 m/s. This can result in large winch line tensions and can result in instability while setting down the pile as well as permanently disturbing the soil in which it is being installed. For a stable and controlled installation, typical penetration velocities need to be 0.25 m/s or less and require the use of active or passive heave compensation and large vents on the pile top to allow water to discharge during self-penetration without blowing out the soil around the pile.

Another installation challenge is to install the mooring system without inducing twist in to the anchor leg and to ensure no damage to the spiral strand wire or polyester rope which has been a recurring problem on deepwater mooring system installations. Mooring line twist can be minimized if a low rotation rope is used on the deployment winch or pair of deployment winches are used to counter-balance the torque. It is also important to ensure twist is minimized during FPSO hook-up and tensioning, as the long-term performance of mooring components under permanent twist is not well understood.

Another very important task during the installation of the SM FPSOs is the hook-up of the vessel to its mooring, especially when considering the persistent swells and high-intensity squalls that may be experienced offshore West Africa. This is even more important if the FPSO is being installed near to a DTU. Up to 6 large bollard pull tugs may be required to position the vessel and it may take approximately 12 - 24 hours to pick up and connect an anchor leg to the FPSO. As indicated above, squalls of up to 29m/s and 39m/s can be experienced in Angola and Nigeria, respectively. In such a squall a FPSO with a large topside facility in ballast condition may experience forces greater than 600 tonnes. In such circumstances even 6 tugs may not be sufficient tugs to hold the FPSO on station at the design heading. In the situation with a DTU nearby this causes some extra restrictions on maneuvering of the tugs. Prior to connecting any lines it is possible to weathervane the FPSO so as to reduce the squall load and so the risk is relatively low. In a similar manner the FPSO can still be weathervaned to an extent with one mooring line connected provided that adequate arrangements are provided to ensure that the mooring line will not “jump” the sheave/shoe, or get damaged. Typically an FPSO to be “storm-safe” for 10-year return period environmental conditions requires 8 – 10 anchor legs attached and tensioned and thus the exposure to extreme weather during hook-up can range from

4 – 8 days. For this duration it is possible that the connected mooring lines will be subject to extreme loads and the vessel to extreme offsets that may result in interference between the anchor legs, positioning tugs and the pre-installed riser/flowline systems. This stage of the installation needs to be properly addressed during design and through installation procedures to ensure a safe installation.

FPSO Fatigue Exposure

Most of the current purpose-built FPSO intended for West Africa are barge-shaped. As discussed by Terpstra et al. (Ref. /3/) there are a number of global strength design challenges associated with such a hull shape. One of these challenges is related to orientation of the vessel with respect to the waves. OWA has a very directional wave climate with swell coming from one direction of up to 75% with very little wave spreading ($\cos^{10}$ or greater) and long periods. Figure 3 shows that about 40% of the swell waves have wave periods larger than 12 seconds. Wave periods in the range of 12 – 15 seconds are close to the vertical bending moment peak, as can be seen from a typical linear FPSO vertical wave bending moment RAO in Figure 10.

Since the timely and confident ordering of steel for the hull structure is key milestone, it is recommended that the hull be designed based on tanker requirements, i.e. North Atlantic for strength and worldwide trade for fatigue (Ref. /4/). When such an approach is followed the inherent safety factors for typical hull connection details, e.g. side shell longitudinals, are relatively high and can well exceed factors of 5 – 10. However, the persistence of long swells tends to drive the fatigue design for main deck and bottom shell connections within the midships region. Therefore, for certain details, such as topside stools, deck penetrations and erection butts, it can create a challenge to ensure that these details are capable of meeting the desired fatigue life requirements when a safety factor of greater than 3 is specified.

Spread-moored FPSO roll responses

Currently there are several large FPSOs being evaluated, fabricated or installed in West Africa. Several of these have production capacities in excess of 200,000 bopd; a revenue stream of US$5 million/day at $25/bbl. Therefore, it is critical to ensure that their design correctly captures all motion responses, particularly roll, to ensure desirable production uptime.

Typically these newbuilding West African FPSO designs have two common characteristics: they are box shaped and have very large topsides which can exceed 35,000 tonnes. Such topsides are also not symmetric in their mass distribution. The asymmetry generates non-zero coupling terms in the mass matrix (pitch-roll and heave-roll) which implies that the FPSO can experience roll motions in head seas. This is presented in Figure 11 and Figure 12 for ballast and fully loaded condition respectively. Since the relative magnitude of the topside mass is greater in the ballast condition compared to the fully loaded condition there is a corresponding drop in the coupling influence.

This is an important aspect to capture when carrying out a hydrodynamic analysis to properly quantify items as:

- Operating roll angles to avoid shut-down,
- Roll damping coefficients through a roll tuning procedure,
- Topside reaction forces,
- Process equipment accelerations and operational angles,
- Intermittent wet and dry surface correction for side shell fatigue analysis, and
- Extreme motions at the connection of risers and flowlines.

It is recognized that topside masses change significantly throughout the design process. However, there is usually sufficient topside mass information available early that will allow the coupling responses to be identified. By properly addressing this aspect early can assist with whether to utilize a bilge keel or not.

The above mentioned roll induced motions comes in addition to the traditional hydrodynamic roll motions due to the fact that the FPSO is spread moored with incident swell angles of ± 25 – 30 degrees relative the FPSO bow/stern. The energy distribution between swell and wind generated waves and their relative headings will also be of importance in determination of the resulting roll responses. Swell will be most important due to the higher period and possibility of roll resonance (15 – 20s). Wave spreading is another parameter which has to be taken into account in determination of resulting roll responses.

Hydrodynamic and Structural Interactions between Floaters

Due to the benign conditions OWA it is possible to choose alternative field layouts with spread moored FPSOs connected e.g. to dry tree units (DTU) like TLP, Spar, barges and also CALM buoys for offloading to shuttle tankers. In addition to the floaters there will be a high number of slender structures (e.g. risers, transfer lines, loading lines, moorings, tendons, riser towers) throughout the water column with different purposes like stationkeeping and transfer of products. All these floaters and slender structures are influenced by each other in some degree. Two types of interactions will be discussed, namely hydrodynamic and structural. A typical example with a FPSO connected to a DTU (TLP) is shown in Figure 4.

Hydrodynamic Interaction

Hydrodynamic interaction will, in this context, imply that the floaters will be influenced by each other such that the altered floater motions have to be catered for in the design of the complete system (floaters and slender structures). Analytically, hydrodynamic interaction between two floaters implies that a matrix system of [12x12] will be needed e.g. for a coupled analysis. Ref. /5/ is one example of a widely used and accepted coupled analysis program.

The distance between the FPSO and the DTU is a key parameter and needs to be determined early in the design. The DTU will for most cases be small (displacement) compared to a large FPSO, hence the influence on the motions of the FPSO will be minor. However, the FPSO, with its large dimensions and displacement, will influence the DTU motions. In order to study this further, some hydrodynamic analyses with WADAM (Ref. /6/) have been performed, covering separation distances ranging from 50 – 200m. Figure 13 shows the underwater sections of the two floaters. The wave headings for the analysis are defined as follows: 0 degrees waves travel from the FPSO towards the DTU and cause the floaters to pitch, 90 degrees waves approach the FPSO at the starboard beam side and results in FPSO and DTU roll motions.

The response amplitude operators (RAOs) at 200 m are very similar to the single body case, especially for wave headings where the incident waves encounter the DTU first. However, at a separation of 50 meters, all wave headings produce changes in the DTU RAOs. These changes are usually in the form of new peaks, and typically occur for wave periods ranging from 5 to 15 seconds. For short waves, the interaction between the two floaters is more important because waves are diffracted and can be generated by both bodies. In the other hand, for long waves, the floater motions follow the waves and therefore, the first order wave responses dominate over the hydrodynamic coupling between the two bodies.

This paper will briefly look into the surge component of the DTU. Figure 14 shows the symmetry in the surge RAOs of the DTU for a single body analysis for different wave headings. For the multi body case, this symmetry is lost due to the presence of the FPSO. Figure 15 and Figure 16 are the surge RAOs with a floater separation distance of 50m and 200m respectively. The 50m RAOs show that the diffracted waves of the FPSO in beam seas produce a small surge response by the DTU, which did not exist for the single body analysis. The diffracted waves of the FPSO in beam seas can be seen in the contour plot of Figure 17. The sum of the incident and diffracted waves yields an effective incident wave angle on the DTU different than 90 degrees, which is responsible for this small new surge component. Similar results and conclusions can be obtained for the other degrees of freedom such as sway and yaw. Other motion responses like heave and pitch can increase by as much as 30% or decrease by 43% depending on the farfield wave heading.

This exercise shows that:

- Hydrodynamic interaction is present both for 50m and 200m separation between the FPSO and the DTU, with the 50m separation as most dominant.
- For swell waves with periods > 12 – 15 seconds, the hydrodynamic interaction is minor for both separations.
- TLP tendon responses and the fatigue limit state (smaller wave periods) should be an important checkpoint with respect to hydrodynamic interactions.

With the usually large (km) distances between the FPSO and the CALM, there will be no hydrodynamic interactions between these two floaters. Another challenging hydrodynamic interaction will, however, be the shuttle tanker's influence on the CALM buoy. Determining the hydrodynamic loading on a free-floating CALM buoy is in itself challenging and coupling it with a weathervaning shuttle tanker is considered even more challenging to analyse. Model testing has usually been the solution used to solve this problem, even though methods and software which should be able to analyze this exist. This paper will, however, not go into more details on this challenge.

Structural Interactions

In addition to the hydrodynamic interactions between two floaters in close proximity, there are also 'structural' interactions. The latter refers to the coupling effects in the dynamic responses of the floaters and slender structures due to the fluid transfer lines connecting the two floaters. For more details in relation to coupled analyses of deepwater floating systems, see Refs. /7/, /8/ and /9/.

Apparently, the connecting lines limit the relative motions of the two floaters and thus influence the floater motion responses. On the other hand, the dynamic motions of the two floaters due to wind, wave and current induce forced displacements at both ends of the connecting lines, and thus drive their dynamic responses. To capture these effects, the two floaters and the associated slender structures need to be solved as an integrated system, and the solution should ensure load phase consistency for the two floaters and the slender structures.

An efficient solution scheme is based on nonlinear time domain finite element method, where the two floaters can be modeled as two master nodes, and the slender structures (risers, mooring and flow transfer lines) as finite bar or beam elements. The dynamic equilibrium of the entire system under environmental loading is achieved at each time step and thus the coupling effects between the two floaters and the connecting fluid transfer lines are automatically included in the solutions. A typical flowchart of how to perform time domain coupled analyses is shown in Figure 18. Careful planning of the coupled analysis is recommended. This implies:

- Selection of which responses are of interest (floater motions, riser, or mooring responses)
- Decision if both wave frequent (WF) and low frequent (LF) responses are of importance.
- Decision if high frequent (HF), e.g. TLP tendon springing is of importance.
- Optimization of simulation model with respect to number of elements and degrees of freedom (e.g. can bending stiffness be neglected for risers and still obtain correct floater motions), such that the analyses can be executed timely.
- Use of selective modeling, i.e. direct inclusion of detailed riser, or mooring in FE model.

Conclusions

- Despite the characterization as benign environment OWA, the combination of chosen field layouts and environments as persistent swell, unpredictable squalls and high surface currents, create specific challenges during the design process. Also, the small ratio between the extreme and the 95% occurrence environmental conditions, results in many aspects of the design of the FPSO system being governed by fatigue loading.
- Spread mooring design requires a detailed knowledge of the riser systems and the environment and the proper evaluation of FPSO global responses in squalls. Proper fatigue life estimation of mooring components is also a very important design issue.
- The installation of an FPSO spread mooring in close proximity to an already installed DTU is challenging with respect to installation time, positioning/maneuvering of tugs and the unpredictable nature of squalls incident on the system. The large number of anchor legs and riser/flowlines also make this a very complex design and procedural issue.
- Benign environment OWA, still the fatigue of the FPSO hull is of importance and needs to be carefully considered and analyzed. However, this needs to be considered in relation to the recommendation of designing the hull according to tanker strength requirements.
- Determination of total roll motion and acceleration is crucial, especially for topside structures/equipment as well as risers hung off on the FPSO sides. In addition to the traditional hydrodynamic roll responses, there are also potential issues related to asymmetry in the large topside masses for these FPSO's and resulting non-zero mass matrix coupling causing roll responses, even for head seas.
- If hydrodynamic interaction between two floaters is present, this has to be taken into account in the design and makes the simulation and design effort more complicated. Structural interactions are handled by using coupled analysis software where all floaters and slender structures are included in the same Finite Element model. Hydrodynamic interactions may, or may not be included in the same coupled analysis.

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Figures

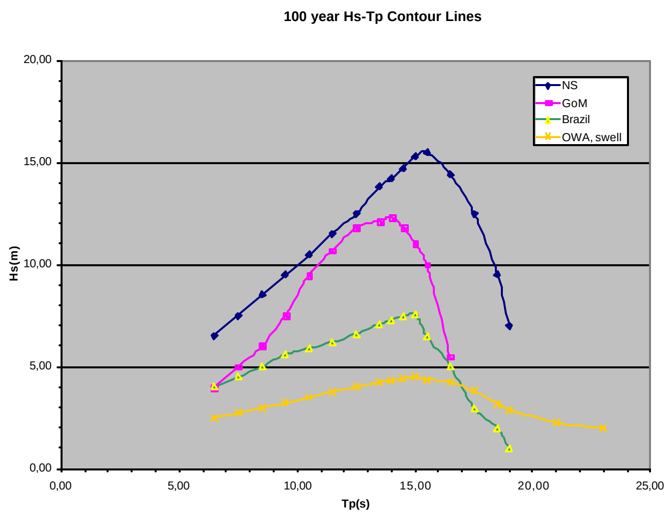

Figure 1 Approximate 100 Year Hs-Tp Contour Lines

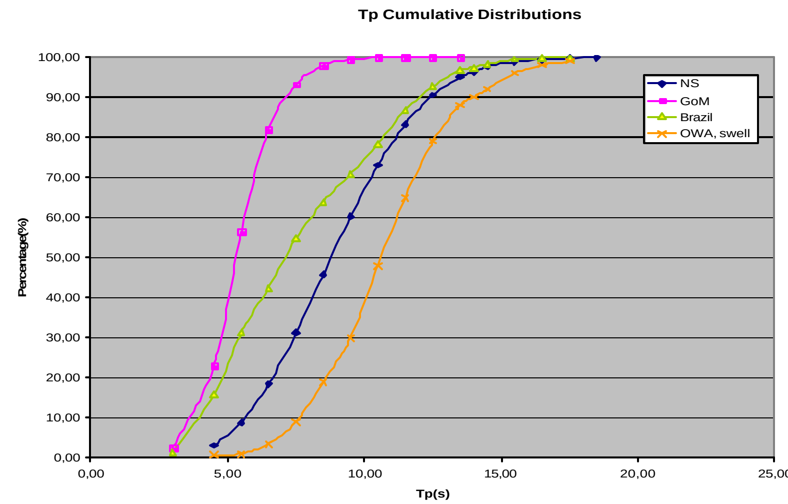

Figure 2 Cumulative Distributions of Peak Periods, Tp

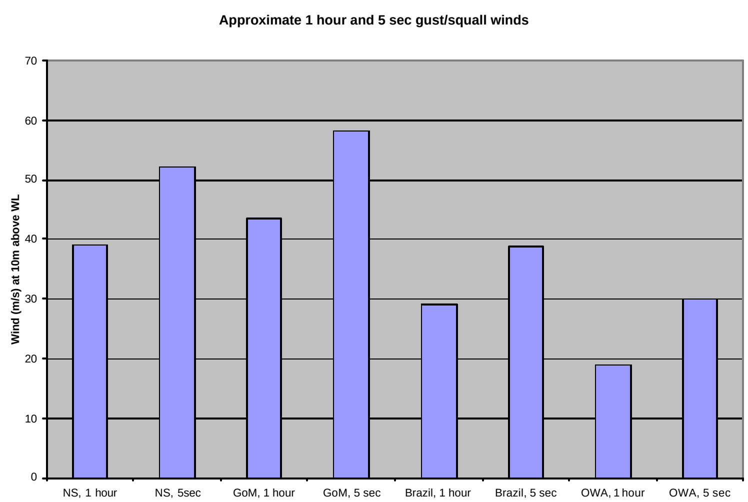

Figure 3 Approximate 100 year, 1 hour & 5 sec Gust Winds (10 m height)

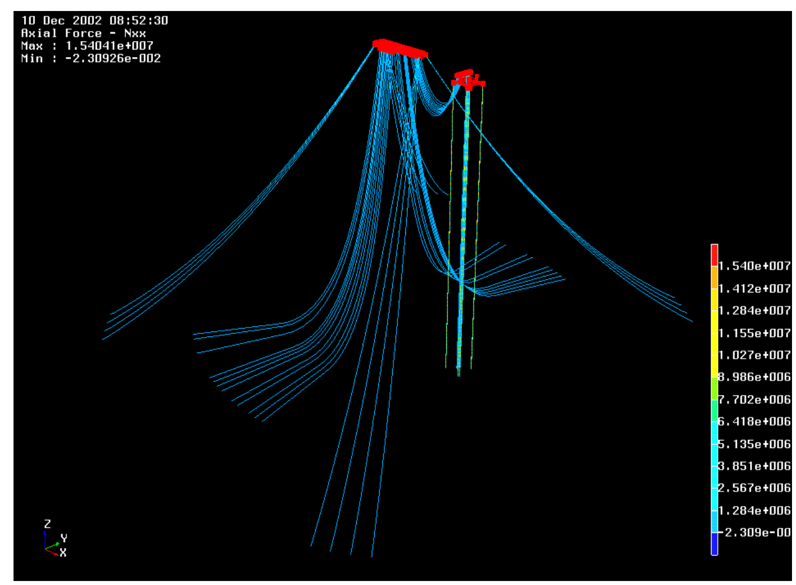

Figure 4 Typical FPSO connected to a DTU (TLP)

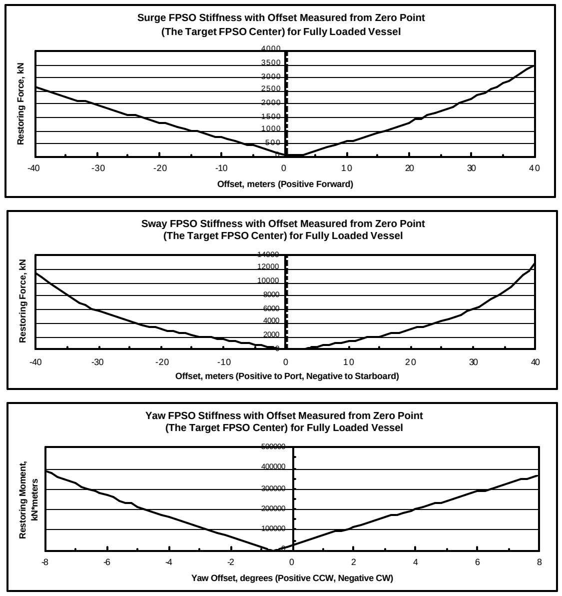

Figure 5 Mooring System Stiffness Curves for Spread-Moored FPSO

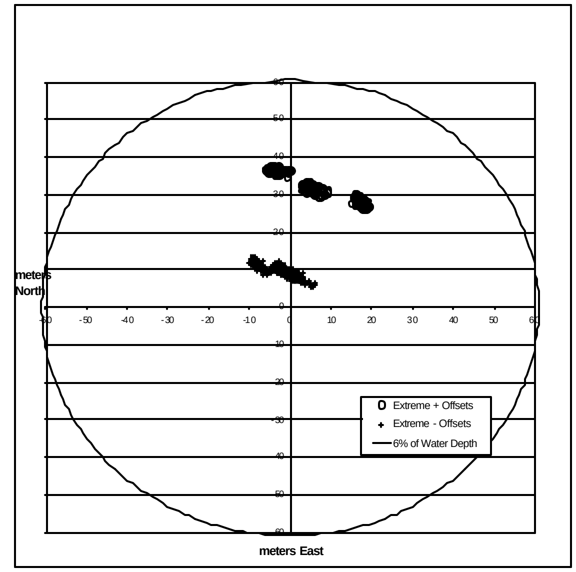

Figure 6 FPSO Midships Offsets in 100-year Swells

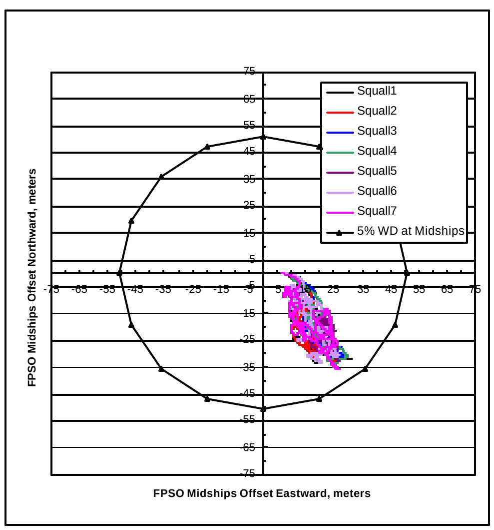

Figure 7 FPSO Response to 7 Squalls (one direction)

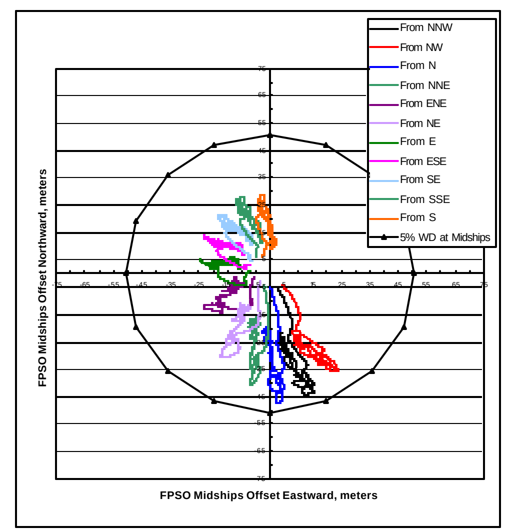

Figure 8 FPSO Response to one Squall (all directions)

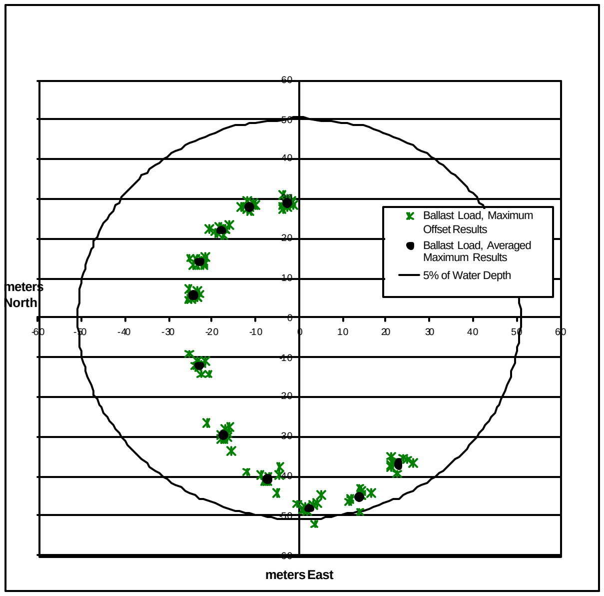

Figure 9 Extreme Excursion Envelope of FPSO due to Squalls

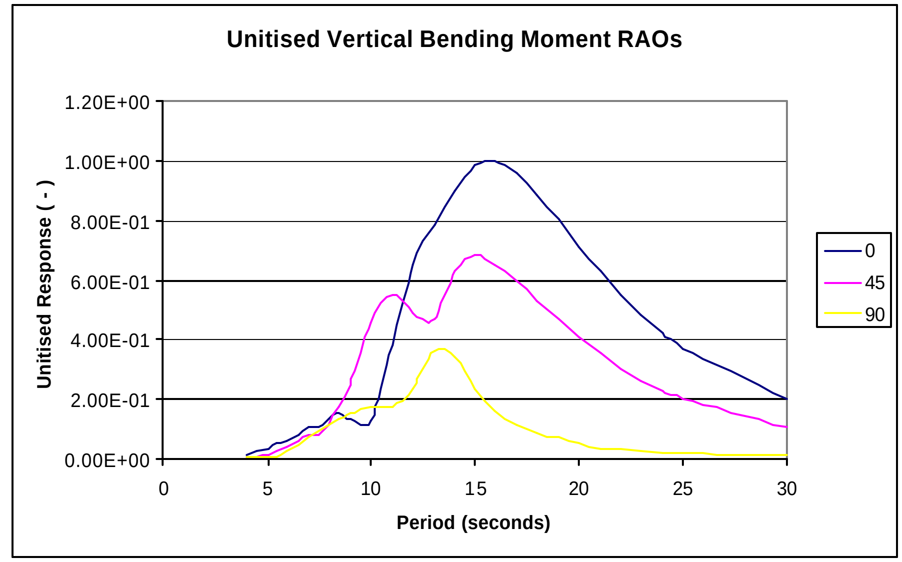

Figure 10 Unitised FPSO Vertical Bending Moment RAOs

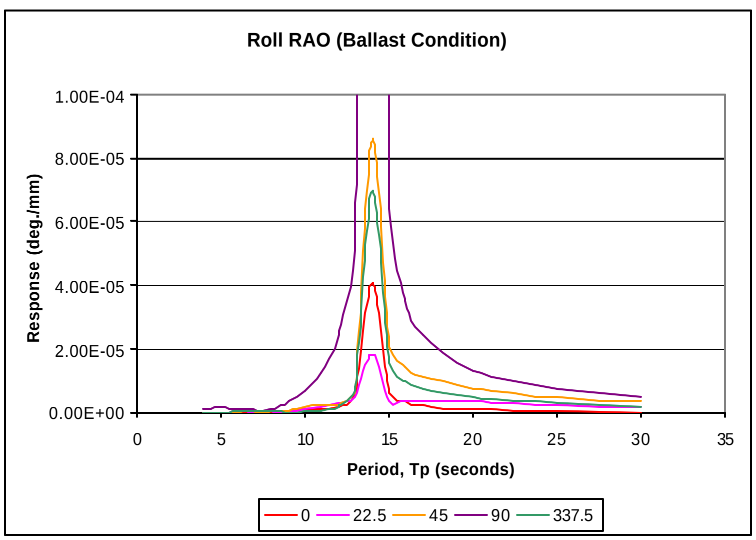

Figure 11 FPSO Roll response in head sea (ballast condition)

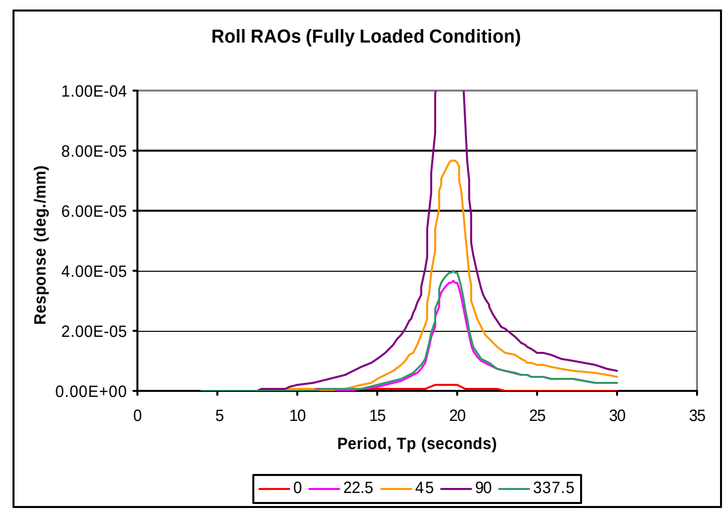

Figure 12 FPSO Roll response in head sea (Fully loaded condition)

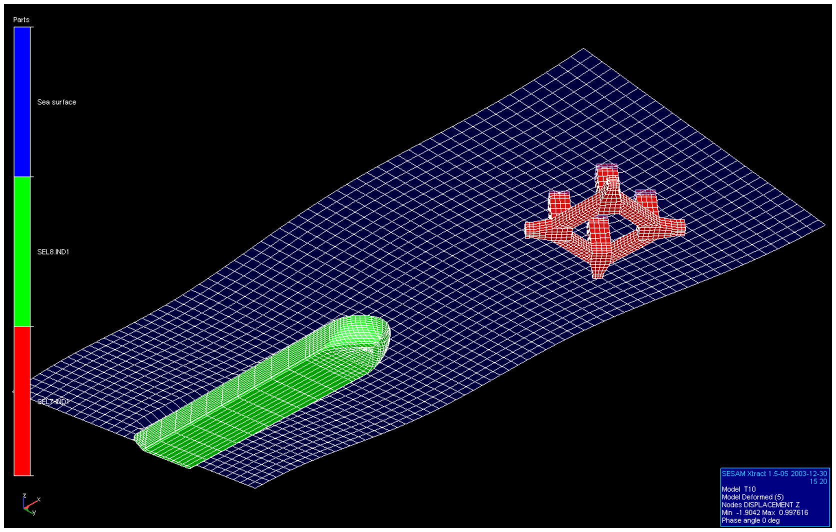

Figure 13 FPSO and DTU (TLP) seen from below

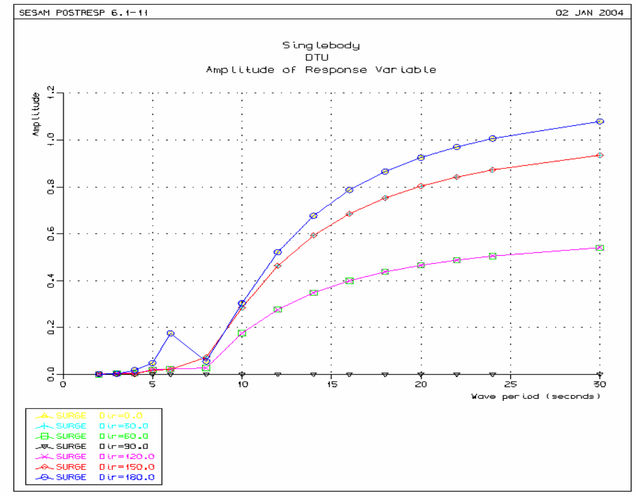

Figure 14 DTU Surge, Single Body

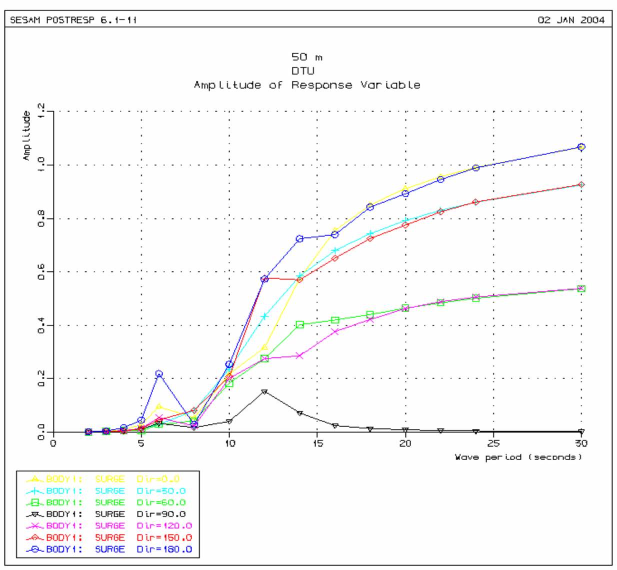

Figure 15 DTU Surge, 50 m Separation

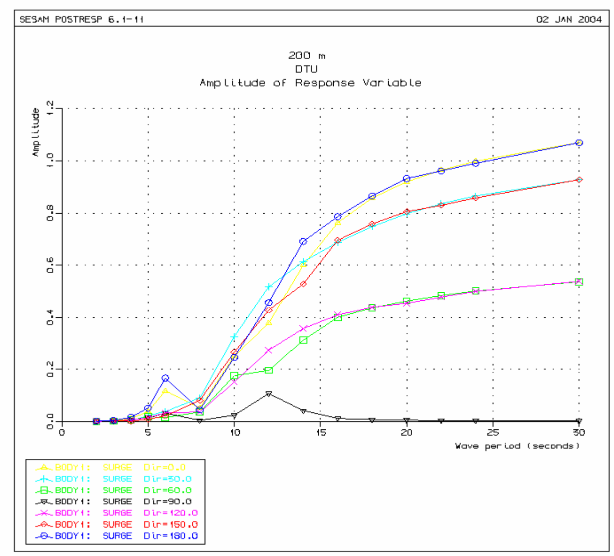

Figure 16 DTU Surge, 200 m Separation

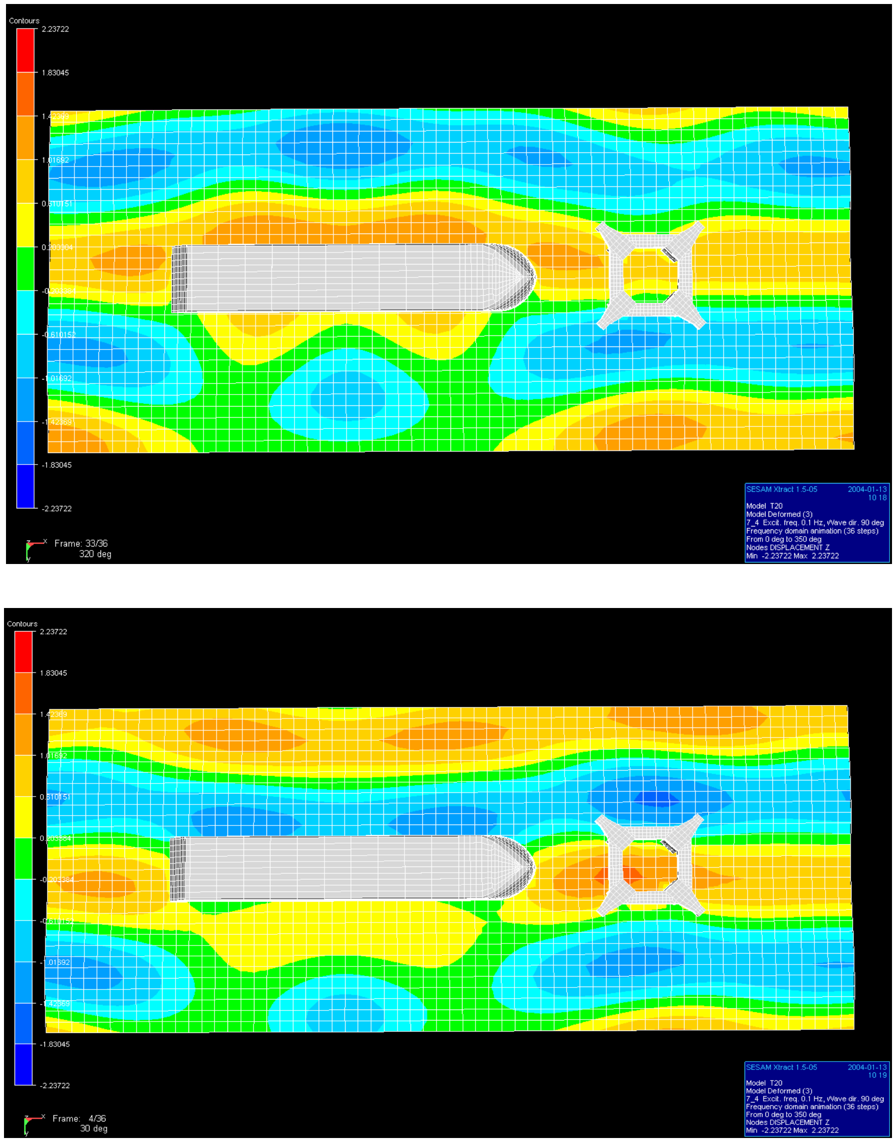

Figure 17 Visualization of Hydrodynamic Interaction

(50 m separation, beam sea, fish view)

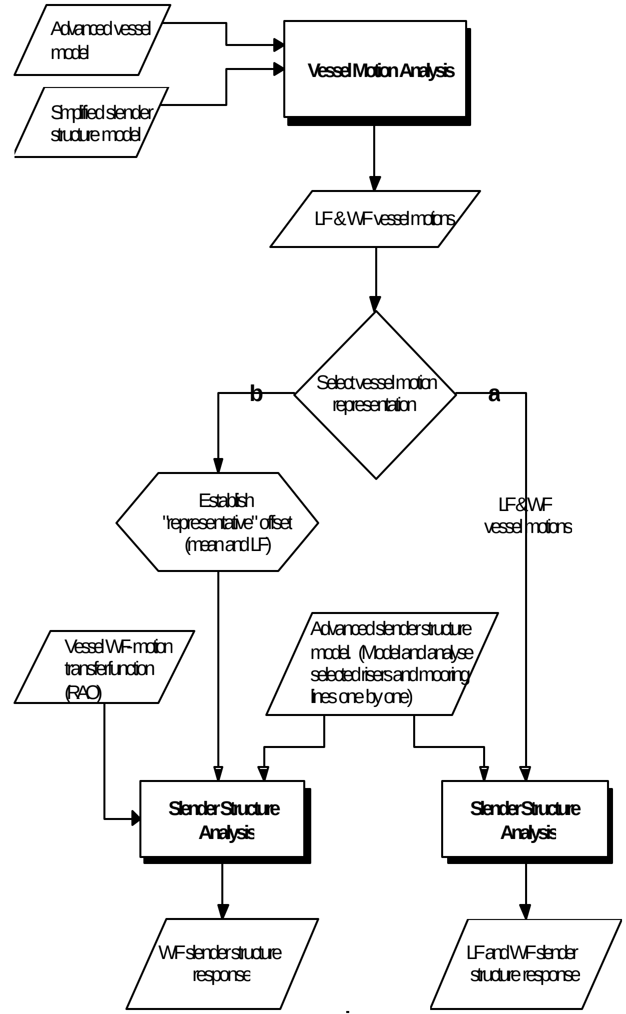

Figure 18 Typical Flowchart for Coupled Analyses