FPSO-TURRET SYSTEM STABILITY AND WAVE HEADING

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ABSTRACT

Turret system positioning is a crucial task in the design of an FPSO. A common approach is to avoid equilibrium bifurcation when the system is subject to current action, in order to assure low levels of mooring forces as well as undesired dynamic behaviour that could lead to excessive loading both on the bearings and on the risers.

Installing the turret near the midship section is a desired trend and doing it whilst preserving the ship´s directional stability can be made possible with the use of passive current stabilisers. This move, on the other hand, has to be investigated for the case when waves and wind are present, as, in this case, the stabiliser may produce an adverse effect.

The present work addresses this point through a case study where the dynamics of a typical VLCC converted into a FPSO and moored to the seabed through a turret system is numerically simulated with a model where wave-current interaction is taken into account.

It has been found that a small degree of instability with respect to current action may reduce wave heading which tend to improve the system´s overall behaviour, as far as mooring forces are concerned. The effect of rudder-type stabilisers on equilibrium bifurcation and on wave heading is discussed and exemplified. A brief discussion on other aspects involved in moving the turret towards midships or installing stabilisers is carried out.

KEYWORDS

FPSO, mooring system, stability, turret, rudder.

INTRODUCTION

Several characteristics of tankers such as large deck areas and storage capacity, as well as market availability, make them a good option for use in oil production at sea. These units are generally named FPSO's (acronym for *Floating Production Storage and Offloading*) and their use, be it newly built or converted, is very well suited for production in projects where large oil processing and storage capacities are required.

Amongst many mooring options for their station keeping , the SPM (Single Point Mooring) of turret type stands out due to the vessel's weathervaning ability (fig. 1).

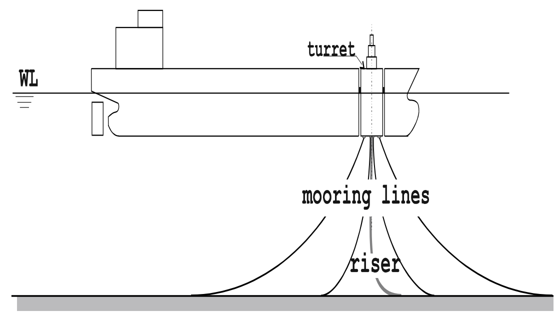


Figure 1 - Turret moored FPSO

However, designing both the riser and the mooring systems of a turret type FPSO is no easy task and studying their dynamic behaviour both qualitative and quantitatively has been the concern of many engineers and researchers in recent years. This work has received intensive support from oil companies seeking to add reliability to their systems and to extend the range of applicability of their design tools. See, for instance, Papoulias and Bernitsas (1988), Garza-Rios and Bernitsas (1996), Bernitsas and Garza-Rios (1996), Nishimoto, Brinati and Fucatu (1996), Fernandes and Aratanha (1996) or Pesce and Tanuri (1997).

One of the aspects that strongly influence the riser behaviour on a turret is its location with respect to the midship section. The closer to the bow the turret is located, the higher the first order excitation experienced by the riser. Therefore, bringing the turret aftwards is a desired trend. Usually when the turret is at the midship section or near it, bow and/or stern thrusters are installed in order to keep the vessel's heading conveniently oriented.

Petrobras standard option for turret moored FPSO's design is to adopt a passive vessel. Consequently, turret location is generally required to be near the bow in order to assure that directional stability is preserved.

In a recent work Leite (1998) investigated the role of rudder type stabilisers in the directional stability of FPSO's by tow testing ship hulls in a tank for different rudder geometries and turret locations. A bare hull case was also performed. In these tests, the turret was simulated by a vertical towing bar with a roller bearing connecting it to the ship model (fig. 2). Here only current action was simulated and the results show that the standard type rudder allows the turret to be installed around 0.36 L forward from midship, where L is the ship's length, without losing directional stability. Further to that a so-called “double rudder” (a rudder with twice the aspect ratio of a standard one) would bring the turret to 0.22 L, an improvement of almost 40% in relation to the original value. On the other hand, if the rudder is removed, the figure goes to 0.46 L, i.e., almost at FP (Fore Perpendicular).

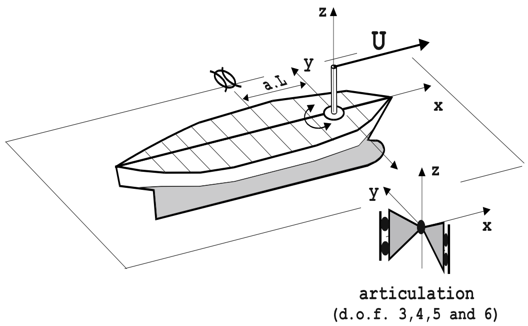


Figure 2 - Directional Stability Test

Results of Thermie, a project sponsored by both Petrobras and the EU for studying the use of SCR´s in FPSO´s, add to this investigation. As part of this project, both MARIN (1998), with their DYNFLOAT software, and the University of São Paulo (USP 1998) through DYNASIM, performed time domain simulations for evaluating the effectiveness of passive stabilisers on the system´s dynamic behaviour. The results obtained show, as expected, that the use of the double rudder, highly beneficial when only current is present, has adverse effects in the presence of waves and wind, when these are not aligned with the current.

While this deterioration does not seem significant in extreme design conditions, its impact on the fatigue life of risers, mooring lines and turret bearings has not been fully evaluated.

These evaluations have also to take into account other important aspects such as deck and structural arrangements as well as storage capacity losses.

The present paper attempts to discuss all relevant aspects in evaluating the use or not of passive stabilisers in passive turret type FPSO design.

HYDRODYNAMIC MODEL

Both the qualitative dynamic analysis (discussion of directional stability of ship shaped vessels and bifurcation of equilibrium) and the time-domain simulations were based on a hydrodynamic model combining short wing and cross-flow principles applied to the hull. This so-called *Heuristic Model* has initially been developed in Leite et al.(1998) and has experimental validation through Captive Model Tests. The model provides expressions for the current loads on a tanker hull as a function of the incidence angle. The expressions so derived are then used for the forementioned dynamic analysis in the case of current only. Aranha et al. (1999) extended the dynamic analysis by superimposing the wave effect to take account of wave-current interaction. The latter model is also supported by experimental results. According to the Heuristic Model, the current-only Moment and Lateral Force Coefficients, $C_{6c}(\alpha)$ and $C_{2c}(\alpha)$ respectively are given by expressions (1) and (2), below:

$$C_{2c}(\alpha) = \left[C_{2c}\left(\pi/2\right) - \frac{\pi T}{2L}\right]\sin\alpha|\sin\alpha| + \frac{\pi T}{2L}\sin^3\alpha + \frac{\pi T}{L}\left(1+0.4\frac{C_B B}{T}\right)\sin\alpha|\cos\alpha|. \qquad (1)$$

$$C_{6c}(\alpha) \cong -\frac{l}{L}C_{2c}\left(\pi/2\right)\sin(\alpha)|\sin(\alpha)| - \frac{\pi T}{L}\sin(\alpha)\cos(\alpha) - \left(\frac{1+|\cos\alpha|}{2}\right)^2\frac{\pi T}{L}\left(\frac{1}{2} - 2.4\frac{T}{L}\right)\cdot\sin(\alpha)|\cos(\alpha)| \qquad (2)$$

The resulting moment on the hull with respect to the turret will be given by expression (3a):

$$\hat{N}_c(\alpha) = \frac{1}{2}\rho U^2 T L^2\left[C_{6c}(\alpha) - a.C_{2c}(\alpha)\right] \qquad (3a)$$

Where:

U : current speed;
ρ : fluid density;
T : ship’s draught;
L : ship’s length;
a : percentage of the ship’s length that defines the turret position with respect to midship.

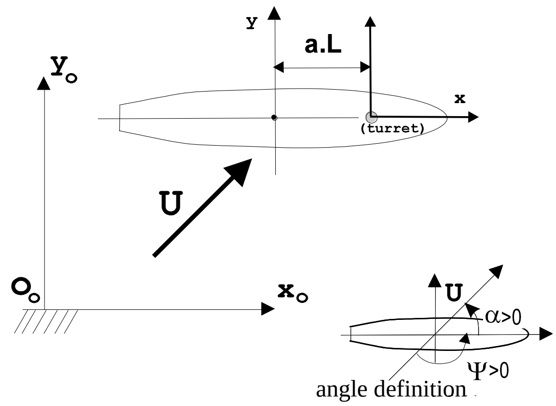


Figure 3 - Ship and earth fixed coordinate systems

Or, in terms of the angle of attack, ψ, where $(\Psi = \pi - \alpha)$ (see figure 3):

$$\hat{N}_c(\Psi) = \frac{1}{2}\rho U^2 T L^2\left[C_{6c}(\Psi) - a.C_{2c}(\Psi)\right] \qquad (3b)$$

In the simultaneous presence of current of speed U and a regular wave train of frequency ω and amplitude A, the second order steady wave drift loads (Forces in the ship’s longitudinal and transversal directions as well as Moment around its vertical axis) causes both a *Doppler shift* in the wave frequency and a refraction in the wave train’s incidence direction (*aberration effect*).

The second order steady wave load vectors, $\mathbf{D}_0(\omega,\beta)$ and $\mathbf{D}_U(\omega,\beta)$ are related according to Aranha’s (1996) formula:

$$\mathbf{D}_U(\omega,\beta) = \left(1 - 4\frac{U}{c}\cos\beta\right).\mathbf{D}_0(\omega_e,\beta_1) \qquad (4)$$

Where:

$\mathbf{D}_U(\omega,\beta)$: second order steady wave load vector when a current of speed U is present;

$\mathbf{D}_0(\omega_e,\beta_1)$: second order steady wave load vector without current;

$\omega_e = \left(1 - \frac{U}{c}\cos\beta\right).\omega$: frequency of encounter;

β : angle between current and wave directions.

$\beta_1 = \beta + 2\frac{U}{c}\sin\beta$: relative angle between current and wave including refraction (*aberration effect*).

Just to exemplify the particular case tested in Aranha et al. (1999), a combination of current from the bow and following waves, $\alpha = 180^o; \beta = \Psi = 0^o$, yield the following expression for the moment with respect to the turret, non-dimensionalised by $\frac{1}{2}\rho U^2 T L^2$:

$$N(\omega,\Psi) = \left[C_{6c}(\Psi) - a.C_{2c}(\Psi)\right] + \frac{gT}{U^2}\left(\frac{A}{T}\right)^2 . \left(1 - 4\frac{U}{c}\right)\left[N_z(\omega_e,\Psi) - a.D_y(\omega_e,\Psi)\right] \quad (5)$$

Where:

g : gravity acceleration;
c = g/ω : wave celerity;
N_z : second order steady wave yaw moment coefficient;
D_y : second order steady wave lateral drift force coefficient;

This expression is easily deducted from simple equilibrium analysis of the turret moored vessel (now considering the second order steady wave loads) and Aranha's (1996) formula.

For general application covering the whole range of angles between current and wave, the complete set of expressions from the Heuristic Model, as well as expression (4) may be used in a time-domain program to compute the time history of a FPSO under simultaneous current and wave action. This was implemented in the simulator used for the present case study.

DIRECTIONAL STABILITY

The directional stability of the ship may be defined as the vessel's ability to keep course with respect to the resulting incident forces and is generally a desired property of the FPSO.

A stable angle of equilibrium of the ship, ψ_E, is defined by:

Current only:

$$\hat{N}_c(\Psi_E) = 0; \qquad \left(\frac{\partial \hat{N}_c}{\partial \Psi}\right)_{\Psi=\Psi_E} < 0. \quad (6)$$

Current + wave:

$$N(\omega,\Psi_E) = 0; \qquad \left(\frac{\partial N}{\partial \Psi}\right)_{\Psi=\Psi_E} < 0. \quad (7)$$

The first expressions of conditions 6 and 7 define the equilibrium position, whereas the second define whether this position is stable or not.

It can easily be seen that $\Psi_E = 0$ is the trivial equilibrium condition and may be defined as the desired condition for the FPSO design. Bifurcation occurs when $\Psi_E \neq 0$. The critical turret position, a_{cr}, after which the system bifurcates, is easily deductible from the Heuristic Model for the current-only case and is given by:

$$a_{cr} = \frac{\left(\frac{1}{2} + 2.4\frac{T}{L}\right)}{\left(1 + 0.4\frac{C_B B}{T}\right)} \quad (8)$$

When waves are present, the expression for a_{cr} will change. The critical turret position will move forwards in the case of following waves combined with head current and towards midship when the current and waves, both come from the bow. Although this qualitative evaluation may be done, no algebraic work was carried out to deduct the expression for a_{cr} in the case of simultaneous occurrence of wave and current.

It is possible to find the different angles of stable equilibrium for the vessel by applying the first expressions in conditions (6) and (7) to equations (3) and (5), the first when only current is present and the latter when following waves are added.

RESULTS OF A CASE STUDY

This section presents a comparative study among different configurations of a conventional FPSO system, distinguished by the turret position and/or the use of two different rudder-type stabilisers. Comparison is based on their horizontal plane dynamic behaviour, in the presence of ocean current, wind and waves. In this analysis, the static current loads are derived from the Heuristic Model, the second order steady wave loads were obtained through linear diffraction theory calculations and corrected according to Aranha's formula (1996) and the wind loads were computed using the Oil Companies International Marine Forum (OCIMF 1993) curves.

The dynamic loading includes both the so-called mooring-line damping and the effect of current-wave interaction, in this case named *Wave Drift Damping* (WDD). This latter effect was again modelled according to the formulation derived by Aranha, (1996).

The dynamic analysis was based on a real turret type FPSO system, recently developed by Petrobras. The vessel is a 270,000 DWT VLCC with a total of 50 risers and 9 mooring lines, for operation at a nominal water depth of 800 m. The system's main characteristics are shown in table 1.

Table 1 - Main characteristics of the VLCC

Characteristics	Loading Condition
Length (Lpp)	320.0 m
Breadth (B)	54.5 m
Draft (T)	21.6 m
Displacement	322078 ton

The effects of two distinct rudder-type stabilisers were evaluated. The first one, from now on called S1, consists of a 24.0 m span rudder whereas the second (S2) has a span of 30.0 m. Both of them keep the original ship's rudder chord of 10.0 m, so their aspect ratios are 2.4 and 3.0, respectively. The original rudder's NACA 0018 wing section was also maintained and a conventional wing theory formulation was applied in order to determine their corresponding lift and drag forces.

STATIC BIFURCATION

A first fundamental result concerns the new critical turret positions, a_{cr}, corresponding to the different stabilisers. Table 2 presents the system's original theoretical and experimental a_{cr} value as well as those with the stabilisers.

Table 2 - Theoretical and experimental values of a_{CR}

Rudder/ Stabiliser	Original (theory/exper.)	S 1 (theory/exper.)	S 2 (theory)
a_{CR}	0.36 / 0.36	0.23 / 0.22	0.18

Figure 4 is the system's bifurcation diagram when only current is present, both for the original rudder and for each stabiliser.

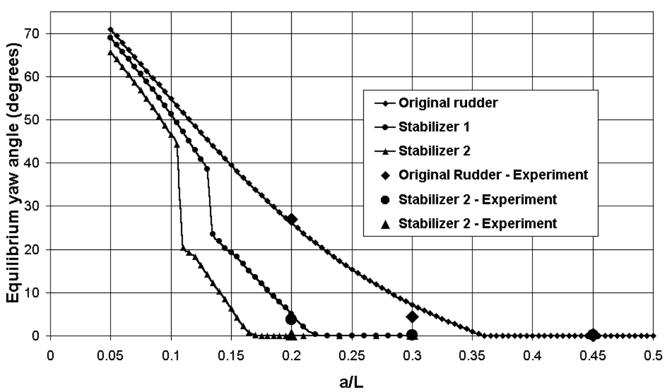


Figure 4 - Bifurcation diagram

It is worth noticing the clear jumps predicted in the FPSO heading angle when the stabilisers are considered. These jumps occur due to the stall effect of the rudders (both stabilisers stall at an angle of attack of approximately 20 degrees). Hence, for higher current incidence angles, the stabilisers loose their efficiency and the predicted heading angle of the system is close to that observed for the original one. It must also be noted that the equations derived from the Heuristic Model incorporate the conventional rudder effects and, therefore, do not predict its stall (to do that the rudder effect must be added separately).

Reminding that the main goal of utilising rudder-type stabilisers is positioning the turret closer to the midship section, without compromising the system's dynamic stability figure 4 may suggest it to be readily achievable by using these stabilisers.

However, improving the system's heading with respect to the current may lead to a deterioration in its heading with respect to the waves when these are not aligned with the current. This fact may most certainly cause an increase in the FPSO's heave motion and, consequently, in the riser system's excitation. This may happen frequently, since non-collinear environmental conditions occur quite often[1]. Risers and mooring system fatigue, discomfort on board the vessel and intensified turret bearing wear may become a bigger issue. To assess this problem, time-domain simulations were carried out considering simultaneous occurrence of all environmental agents.

TIME-DOMAIN SIMULATIONS

The main aspect analysed in the time-domain simulations was the ship's heading angle with respect to the wave direction. This angle provides a direct measure of how the ship's overall behaviour will be when using stabilisers, for different turret positions.

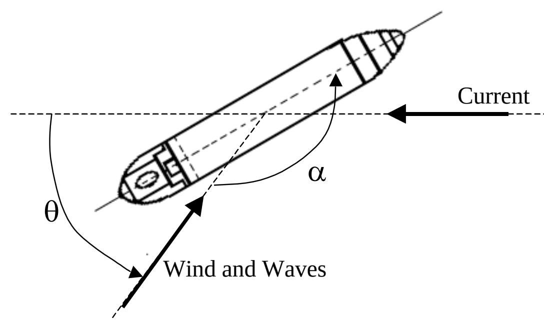
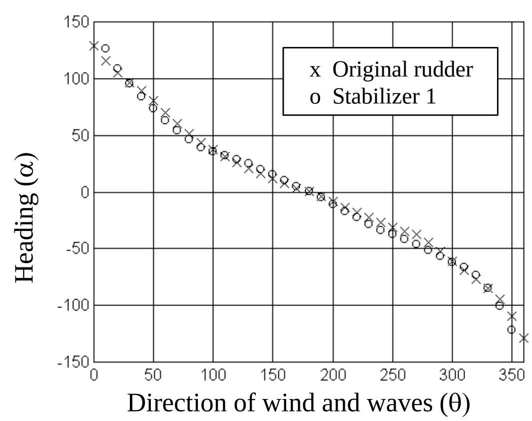


Figure 5 – Angle definitions for time-domain simulations

Figure 5 illustrates the angle definition for time-domain simulations: α is the relative heading with respect to wave direction[2] and θ is the absolute wind/waves direction angle, measured relative to the ship's initial position (for instance, $\theta = 0^o$ for following sea). All simulations assume the following initial condition: the ship is always aligned counter-current or, in other words, the initial angle of incidence of the current with respect to the ship's longitudinal axis is always 180° and, thus, $\theta = 0^o$ or $\theta = 360^o$ means that current and wind/waves are in opposite directions whereas $\theta = 180^o$ is the current/wind/waves collinear case (for which $\alpha = 0^o$, an angle that may be stable or not depending on the type of equilibrium encountered).

The main results obtained are graphically represented by figures 6 to 9. The horizontal axis in the figures cover the whole set of possible relative angles between waves and current directions, ranging from -180^o ($\theta = 0^o$) to $+180^o$ ($\theta = 360^o$).



[1] Collinearity of current, waves and wind are prone to happen during extreme storm conditions but not in milder situations.

[2] Wind and waves are assumed to be always collinear.

Figure 6 - Ship heading w.r.t. waves x angle between current and wind/waves a = 0.45 (original rudder x S1)

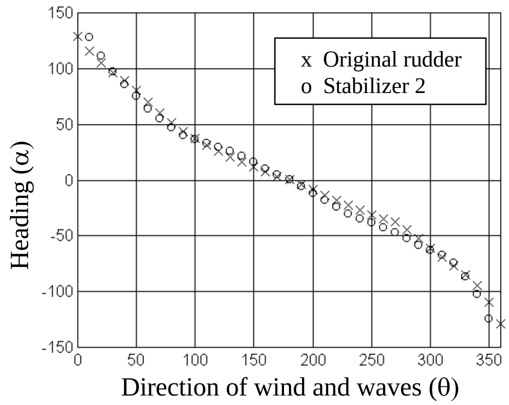


Figure 7 – Ship heading w.r.t. waves x angle between current and wind/waves a = 0.45 (original rudder x S2)

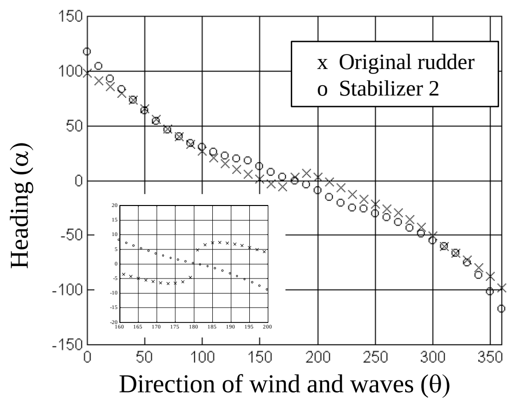


Figure 9 - Ship heading w.r.t. waves x angle between current and wind/waves a = 0.20 (original rudder x S2)

In order to assure a realistic approach to the performed analysis, the assumed current intensity corresponds to the most severe extreme current in Brazil's Campos Basin (current coming from NE direction). For each angle θ considered in the simulations, the respective real extreme waves characteristics (zero up-crossing period, T_z, and significative height, H_s) related to that direction, obtained from the area's oceanographic tables were used. For this reason the results presented are not symmetric with respect to the 180º direction.

The first FPSO configuration analysed assumes a conventional turret position, placed near the bow. Figures 6 and 7 represent the system behaviour for a = 0.45 (a.L = 144 m). Figure 6 compares the system with original rudder to the system with stabiliser 1 (2.4 aspect ratio). Figure 7 presents analogous results for stabiliser 2 (3.0 aspect ratio).

The results clearly demonstrate that the stabilisers do not influence significantly the wave heading for the a = 0.45 configuration. The high restoring moment provided by the large value of "a" governs the ship's heading angles.

The same analysis was performed for a turret position closer to midship (a = 0.20). The results are presented in figures 8 and 9.

Some important changes in the system behaviour may be observed. First of all, the ship's heading angles w.r.t. the wave are now smaller, if compared to the a = 0.45 case. This fact was already expected since the steady second-order drift moment provided by the waves action is now comparable in magnitude to the steady current restoring moment. Figure 10 illustrates this fact by comparing the heading angle, α, for the ship with original rudder both for the turret at a=0.20 and 0.45. The second significant change was also expected: the effect of the stabilisers on the ship's final yaw angles is now stronger. The stabilisers contribute to increase the angle w.r.t. waves when simultaneous and non-collinear current and wind/waves are present.

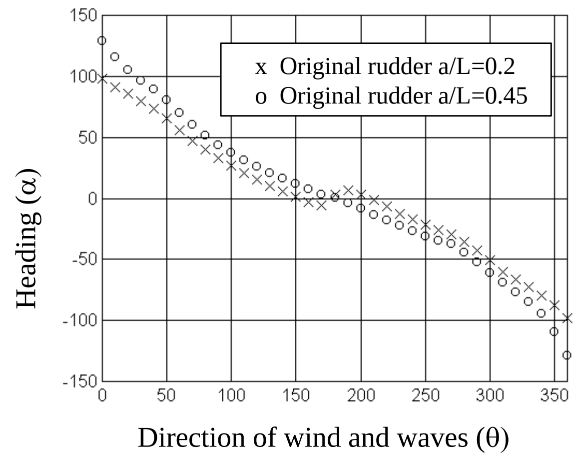


Figure 10 – Ship heading w.r.t. waves x angle between current and wind/waves (a = 0.45) x (a = 0.20) - original rudder

Nevertheless, although these differences are now measurable, they may not be high enough to represent a major change in the system's overall behaviour from a practical point of view. It might be readily seen from the figures that the maximum increase in the heading angle α (compared to the system with conventional rudder) is approximately 10 degrees for stabiliser 1 and 15 degrees for stabiliser 2.

Finally, another aspect shall be addressed: the effects of equilibrium bifurcation. According to table 2, the critical turret position for the original system is a_{crit}=0.36. Therefore, the trivial initial position assumed is, for such system, unstable. The zoom charts presented in the left side of figures 8 and 9 allow a better visualisation of the bifurcation phenomenon. For the system with stabiliser 1, the a_{crit} value corresponds to 0.23, what means that a "weak" bifurcation of the equilibrium angle shall occur whereas, for the system with stabiliser 2, equilibrium bifurcation does not exist (a_{crit}=0.18).

The system with the original rudder bifurcates at θ=180º and its behaviour may be illustrated as follows: let's consider, for example, the original FPSO system subject to an initial wave incidence angle of θ = 190°. Figure 11 shows the initial and final positions of the system for this particular case.

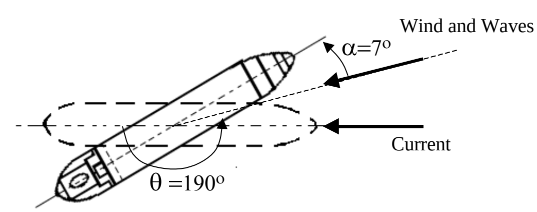


Figure 11 - Initial and final positions of the ship

It may be seen that the ship heading increases and crosses the wave direction plane, leading to a final positive angle α of approximately 7º. This final position is dictated mainly by the system static bifurcation aspects. The same kind of result is obtained for initial wave incidence angles θ in the range 150<θ<210 (approximately). It is interesting to observe that for θ ≅ 150º or θ ≅ 210º (what means a initial wave heading of ±30º), the final equilibrium position of the ship (a=0.2, conventional rudder) is aligned with the waves direction (α=0).

The results clearly indicate that the effects of a rudder type stabiliser on the overall dynamic response of a typical FPSO system subject to combined current, wind and waves action are small. Although the rudders confer a considerable gain to the system stability w.r.t. the current, the increase in the wave heading is not large enough to cause problems, at least for the Campos Basin typical extreme environmental cases considered.

Nevertheless, the preceding results consisted mainly of comparisons between systems with the same turret configuration. Figure 12, on the contrary, compares the wave heading response for the FPSO with usual turret position (a = 0.45L) and conventional rudder to that obtained for the system with the turret placed closer to midship (a = 0.20L) and with stabiliser 2 incorporated. It becomes clear, from the figure, that the heading response is similar for both configurations.

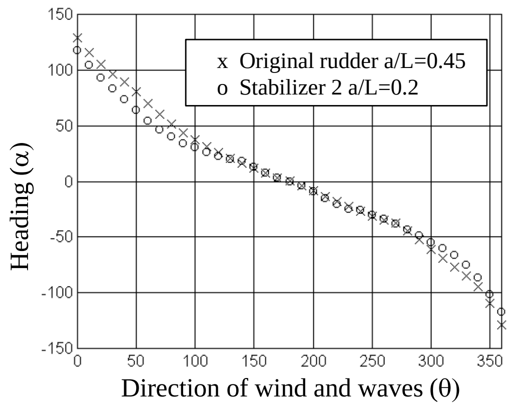


Figure 12 – Ship heading w.r.t. waves x angle between current and wind/waves a = 0.20 with S2 x a = 0.45 with original rudder

Yet a final aspect shall be added to the discussion. Despite the performed analysis considers the whole range of possible angles between current and waves (from –180º to +180º), the current-waves aperture angle usually does not exceed ±45° in extreme environmental conditions offshore Campos Basin. This corresponds to those cases restricted between θ=135º and θ=225° for which, the ship's maximum heading angles w.r.t. waves are not greater than 20 degrees, which may be considered a reasonable value.

However, there are some milder conditions that may lead to undesirable wave headings. For example, in Campos Basin there is a relatively common non-extreme condition composed by swell waves, which comes mainly from the south, in the presence of current coming from the north (or north-east) direction. In such case, the angle between waves and current is typically close to 180 degrees and, depending on their relative intensities, the FPSO may be subject to beam-sea waves around 4.0 meters high. This situation may not be acceptable, depending on the design parameters assumed, but it does happen for any of the FPSO configurations considered in this analysis, with or without the stabilisers and, to avoid it, only tug assistance or lateral thrusters may be the solution.

OTHER ASPECTS

Besides the system's dynamic behaviour, other aspects have to be considered when deciding the turret position along the ship. These aspects will be briefly discussed now, from an Oil Company's point of view.

DECK ARRANGEMENT

Depending on deck area and production plant size, bringing the turret towards midship may require the plant to be divided in two pieces: one forward and the other aft of the turret.

From a process flow point of view this is an undesirable trend, however, some advantages may also be devised. An example is the flare arrangement. Petrobras standard in FPSO design has been to place the accommodations astern and the flare forward, at the bow. In conventional turret arrangements, the flare will, thus, be located near the riser top connections, a gas-rich area. By moving the turret aftwards, this aspect is improved.

Petrobras has recently evaluated the impact on the plant arrangement of bringing the turret to a=0.20. The conclusion was that it is not an impeding aspect neither technically nor economically.

STRUCTURE

The structure of a ship near the bow tends to be locally more appropriate for installing a turret than near midship. This is specially true in conversions, where an existing tanker has the fore peak bulkhead and, as the beam is reduced near the bow, the ship sides offer a natural stiff connection for the turret structure and the bending moment in the transversal plane will be small. Mainly shear forces will be present in transmitting tension to the ship's hull structure. A smaller amount of structural reinforcements may, therefore, be expected.

Installing the turret near the midship section will, on the other hand, demand more structural reinforcements. Fatigue may be of concern, as a quite stiff vertical cylinder (the turret shaft) will be inserted into a relatively soft surrounding structure. As the ship's beam reaches its maximum in the midship section, transversal bending will be higher.

No specific evaluation has yet been made by Petrobras for comparing the two options from a structural point of view. To get to a final conclusion, a quantitative analysis has to be carried out taking both weight and costs into account.

STORAGE CAPACITY

The final aspect to be considered is how storage capacity will be affected by moving the turret to the centre. Near the bow very little loss is expected, since fore tanks are smaller and some intended for ballast.

On the other hand, the large tanks located near the midship section will partially lose their oil storage purpose, both because of the turret and because of the need for building cofferdams around it. However, large tankers, above 200,000 DWT, are available for conversion in the international market and, typically, Petrobras' FPSO's are in excess of the needed storage capacity, taking offloading intervals and production capacity into account.

Typically, Petrobras FPSO's are converted 280,000 DWT to 320,000 DWT tankers, and the largest plant to be installed will produce a peak liquid throughput of 200,000 Bpd, out of which, 180,000 barrels of oil. Offloading intervals in Campos Basin are of 6 days (including the offloading operation itself, that lasts 24 hours) and a safety margin of 2 days is normally specified. Considering a tank utilisation factor of 90% plus an oil of 0.94 t/m^3 density, the needed storage capacity reaches around 210,000 DWT, leaving a good margin for capacity loss in these vessels.

When new built FPSO's are to be considered, the design can account for the peculiarities of a central turret from the very conceptual phase and capacity losses or, in this case, increasing the size of the vessel, can easily be minimised.

CONSTRUCTIVE ASPECTS OF A DOUBLE -RUDDER

The option for a so-called "double-rudder" or any stabiliser with larger aspect ratio than the original rudder will lead to some problems regarding its construction and installation. If the vessel is to be new-built, this problem may be reduced but in conversions, which has until now been the standard option for Petrobras, it becomes more complex since the new stabiliser has to be adapted into an existing stern arrangement.

Fernandes et al. (1998) discussed this aspect and presented an interesting option for the adaptation of a "double-rudder" into an existing VLCC. The proposed solution is shown in figure 13. The idea is to install a hinged twin rudder below the existing one via simple changes in the stern-post. Nevertheless, some local reinforcement and a re-analysis of the stern structure will certainly be needed.

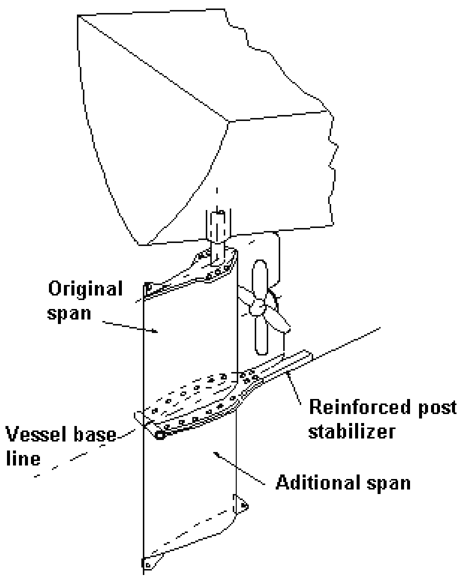


Figure 13 - One possible arrangement for the introduction of the stabiliser on existing hulls

The hinged twin rudder was devised as a way to suit draught limitations in the shipyard and its surrounding area. Its installation is quite simple and the lowering operation may be performed via wire-pulley mechanisms after arriving at the location.

CONCLUSIONS

The paper discusses the use of bow or central turret in turret moored FPSO's with passive station keeping systems (passive mooring system). The main focus was placed on the directional stability of the vessel and its consequences on the relative angle between the ship and the incoming waves, since, in general, as this angle increases, so will the first order excitation on the risers.

The hydrodynamic loading as well as the dynamic response of the vessel, subject to combined current, wind and wave action, are discussed in the light of the rudder effect and the position of the turret along the centreline of the ship.

From a wave heading point of view, it was shown that the turret installed at 20% of the ship's length forward of the midship section combined with a rudder type stabiliser is equivalent, or even slightly better in terms of overall behaviour, to the standard practice of installing the turret at 45% of the length forward of midship with the original rudder (see figure 12).

On the other hand, figure 10, where the ship with the turret at a=0.20 and 0.45 , both with the original rudder, are compared, may even suggest that a small degree of instability may be acceptable, or desirable, since the unstable system shows a better behaviour regarding the relative angle between the ship and the incoming waves than the stable one. However, this apparent advantage needs further investigation. The simulations only took care of extreme conditions and an unstable system may show disadvantages in milder conditions where riser and mooring system fatigue is a major issue.

No investigation was carried out in order to assess the possible improvements obtainable with the rudder operation. In all cases analysed the rudder was assumed to be fixed, aligned with the ship's centreline. Under current-only conditions the rudder operation would be useless as the instability is symmetrical (i.e., turning the rudder would only force the ship to bifurcate to the other side), but when all environmental agents are present the rudder may be operated to bring the vessel to a more adequate heading towards the waves.

Other aspects involved in installing the turret near the midship section were raised and briefly discussed, mainly regarding the converted FPSO case. It becomes clear that a bow turret offers some advantages in terms of structural/deck arrangement and storage capacity.

To conclude, it is important to emphasise that the main drive in bringing the turret towards midship is to lower first order riser excitation. However this cannot be done without looking at the problem as a whole, i.e., not only extreme conditions, as addressed in this paper, but also from a fatigue point of view. To do that, milder non-collinear environmental conditions need to be addressed.

The final decision on whether to install the turret at the bow or not, and with which type of stabiliser (passive or active), has to be taken based on the specific case analysed. Nevertheless, it has been shown that directional stability is easily obtainable with simple passive stabilisers and that the supposed deterioration of the ship's heading w.r.t. the waves is not significant. Moreover, comparing the cases where a=0.20 with stabiliser 2 and a=0.45 with the original rudder (Petrobras' standard practice), the first one shows better results regarding ship's heading in extreme conditions. Further improvement may be obtained through rudder operation.

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