Stability of Deepwater Drilling Semi Submersibles

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Abstract

Most stability standards for the design of semi-submersibles are based on quasi-static approaches. These methods do not take into account the dynamic wind and wave loading and the resulting platform response. Several model tests in recent years revealed that stability criteria of drilling semi-submersibles are influenced by the existence of nonlinear wave loads. These wave loads appeared to be induced by shallow water wave effects on top of the pontoons. This paper reviews these effects from model tests, from numerical calculations and from field experience concluding that for increasing natural periods of roll, the low frequency response increases. These motions reduce the availability of the unit for drilling operations. The authors share this experience in hope that designers of new semi-submersibles will take these dynamics into considerations.

Keywords

Stability; Semi-submersible; Operability; GM; Roll motions; Nonlinear wave loads.

Introduction

Classically the major concern during semi-submersible design is to ensure that the vessel will have adequate intact and damage stability. With the advent of watertight upper decks and larger columns, the stability of some new semi-submersibles is governed by having an intact GM greater than 0m, rather than the shape and area under the GZ curve as was usually the case with older designs. While this makes for a robust design from a stability aspect, it does not make for one from a motion point of view.

At low GM values, it has been observed that 5th generation semi-submersible designs typified by shallow drafts and large pontoons are susceptible to large angles of roll and pitch due to their long natural periods and subsequent low-frequency response [Voogt, 2002]. Martin and Kuo [Martin, 1978] observed this phenomenon for semi-submersibles in regular beam waves. Takaki and Higo [Takaki, 1990] also observed low-frequency sub-harmonic rolling motions during model tests on a semi-submersible in regular waves. These motions were related to the steady tilt angle of the unit, increasing as the steady tilt angle increased. Despite the high level of research interest in steady tilt and low-frequency motions, until now there was little documented evidence of such problems occurring in practice. This paper aims to bridge this gap between research and operational experience. After a review of the theoretical hydrodynamic background and the numerical methods available to assess these phenomena, the operational experiences and implications will be discussed.

Hydrodynamic Aspects

Submerged pontoons of a semi-submersible are subjected to upward forces proportional to the wave drift force [Pinkster, 80], [Molin, 79]. This force increases as the pontoon comes closer to the free surface.

In addition to this wave drift force-induced lift, an additional lift force exists on submerged pontoons. This lift force is due to currents and eddies being shed from the pontoons and columns. The impact of these eddies is well known for horizontal motions of FPSOs (Galloping/Fishtailing) and Spars (VIM), but with low restoring moments these phenomena can also result in angular motions of the platform.

Tests in Regular Head Waves

In theory, in regular head seas there is no roll excitation, but the system is fundamentally unstable. If one pontoon (either pontoon) becomes slightly closer to the water surface than the other, then the vertical wave drift force on it will increase. The difference between this vertical wave drift force and the vertical wave drift force on the other pontoon will cause a static heel angle.

Therefore, for a semi-submersible with low initial stability (low GM), the difference in vertical wave drift forces on the pontoons may provide an overturning moment that is large enough to require a substantial
angle of heel to develop an equal restoring moment. A larger value for initial stability will obviously reduce the equilibrium angle of heel. This angle of heel is only found in regular wave tests in head seas or very close to head seas. To demonstrate the dependency of angle of heel on a representative design wave period, model tests were carried out with periods from 7 to 23 seconds and increasing wave height [Voogt, 2002]. Figure 1 shows how the mean roll angle varied over these wave periods at the operating draft with 2.5m GM in 3 knots current. From this data it can be concluded that the maximum list for this configuration occurs at a specific wave frequency of approximately eight seconds.

**Fig. 1: Mean list angles observed in regular waves at different periods, measured in 3 knots current**

**Low Frequency Roll Motions**

In irregular (long crested) waves, the effect is much less pronounced. The vertical wave drift force is not constant and variations in force on each pontoon are equal to or larger than the force differences due to the pontoon immersion depth difference. However full scale monitoring confirms that the effect of low GM can be seen in the actual roll motions a vessel experiences in head waves. As shown in [Voogt, 02] these motions increase:

- for relatively short waves (wave period 7s to 10s)
- not linearly or quadratically with the wave height
- rapidly with current present
- with decreasing pontoon submergence

Figure 2 shows the measured roll motions in irregular head waves during a 1-year Gulf of Mexico storm condition (Hs=3m, Tp=8.2s) with 1 knot current for a GM of 2.5m. These roll motions mainly show a low frequency part at the natural period of 60 seconds. These motions are induced by nonlinear wave loads, as discussed in the section on the numerical background.

**Fig. 2: Low Frequency Roll Motions measured for low GM values in operational head waves**

**Effect of Stability**

In an operational sea condition with significant wave height of 3m and 8.2 seconds peak period, the roll motions of the GSF Development Driller hull were measured for head waves with 3 knots parallel current. The standard deviation was shown for a GM of 2.5m and 5m. Additional research showed that the increase in the roll motions is not linear with the change in stability (see Figure 3). These roll motions occur mainly around the natural frequency of the semi-submersible. For smaller GM values this period increases, and thus the damping and wave excitation change.

**Fig. 3: GM versus standard deviation of roll motions**

**Decay Tests**

To assess the damping with different GM values, roll decay tests were carried out. The natural periods and damping values for each test were derived by the process of fitting the equations of motion with zero external force to the measured positions and derived velocities ($\dot{\phi}$) and accelerations ($\ddot{\phi}$):

$$I_{xx} \cdot \dddot{\phi} + b_{lin} \cdot \dot{\phi} + b_{sec} \cdot |\dot{\phi}| \cdot \ddot{\phi} + GM \cdot g \cdot \text{disp} \cdot \phi = 0$$

in which $I_{xx}$ is the total roll inertia (including the added inertia) and disp is the displacement in tonne. A low pass filter is used right above the natural frequency for the time derivatives of the roll motions. The estimated total inertia provides the natural frequency and the estimated linear (blin) and quadratic (bsec) damping terms can be used to calculate the equivalent damping (beq) as percentage of the critical damping (Bc) as follows:

$$b_{eq} = (b_{lin} + b_{sec} \cdot |\dot{\phi}|) \cdot 100\%$$

in which $|\dot{\phi}|$ is the absolute roll velocity in deg/s.

The critical damping follows from:

$$B_c = 2 \cdot \sqrt{I_{xx} \cdot GM \cdot g \cdot \text{disp}}.$$

To find the optimum estimate for the damping, a least square estimate is used.
The damping is given as a percentage of critical ($B_c$).

The total absolute damping for a specific roll velocity ($\dot{\phi}$) equals:

$$B_\phi = B_{eq} \cdot B_c = (b_{lin} + b_{sec} \cdot \dot{\phi}) \cdot B_c$$

$$B_c = 2 \cdot \sqrt{I_{xx} \cdot GM \cdot g \cdot \text{displ}}$$

in which $I_{xx}$ is the total roll inertia (including the added inertia) and displ is the displacement in tonnes.

When reducing the GM from 5.0m to 2.4m, an increase in the natural periods from 40 to 65 seconds was measured. For the cases with GM above 4m linear damping could be fitted to the data, but for smaller GMs the roll damping became more quadratic. For those cases a least square fit with linear (equivalent) damping only is no longer accurate to reproduce the motion behavior and is not accurate to predict the roll motions in numerical calculations. Figure 4 shows how quadratic damping terms are required to properly predict the roll response when the semi-submersible had low initial stability and a long natural period.

**Numerical Background**

Prior to the tests, a diffraction analysis on the vessel was completed for both drafts. This analysis demonstrated that at headings just off 180 degrees the roll drift moment was comparable to the vessel righting moment in the regular wave test at the survival draft. The diffraction analysis also showed that for a heading slightly off from head seas (165 degrees) at operating draft the roll drift moment quadratic transfer function (QTF) is much smaller when compared to the survival draft (Figure 5). This characteristic has been attributed to the pontoons being immersed deeper into the water. This force is best known for causing hovering submarines to rise to the surface [Wu, 93].

A further observation from the diffraction analysis was that as the vessel heeled over the vertical wave drift forces for wave periods of around 7 seconds increased even further.

![Figure 4](image_url)

**Fig. 4:** Measured roll decay at GM=2.4m with fitted equation of motions accounting for linear damping (upper graph) or combined linear and quadratic damping (lower graph)

**Fig. 5:** Comparison of roll mean wave drift moment QTF at operating and survival drafts - wave direction 165 degrees

The diffraction analysis was performed with the vessel heeled at 3 degrees, and the results shown in Figure 6 when compared to the vertical drift forces at the even keel condition show a considerable increase. When comparing the roll mean drift moment QTF at even keel with the rig heeled at 3 degrees, the peak of the QTF at 3 degrees is almost 4 times higher with an increased bandwidth also.

![Figure 6](image_url)

**Fig. 6:** Increase in the roll mean drift moment QTF between vessel at even keel and at three degree roll angle

Therefore, it could be said that a small roll drift moment at even keel could cause a small list angle, subsequently the roll drift moment increases rapidly and the problem becomes significant. For comparison, the stability curve of the semi-submersible is shown in Figure 7. It can be seen that at 0 and 3 degrees heel the wave drift overturning moment is greater than the rigs roll restoring moment, and therefore causes the rig to heel until equilibrium is reached. It should be noted that without the model tests to calibrate the diffraction analysis results, it would be difficult to determine whether this phenomena would actually occur or not. The diffraction analysis results would suggest a final list angle of greater than six degrees when compared against the roll restoring moment of the rig, particularly for the six-meter wave height case. The reason the rig did not list any further is that with a six degree list and a wave height of six meters the top of the pontoon becomes
exposed, something that cannot be observed using the calm water roll restoring moment curve.

![Figure 7: Increase in the roll mean drift moment QTF between vessel at even keel and at three degree roll angle](image)

In essence, these results suggest that, at small heel angles, the higher pontoon experiences a greater steady vertical force than the lower one, thus resulting in a net steady moment. Equilibrium is achieved when there is a balance between this steady wave-induced heeling moment and the hydrostatic restoring moment. If the rig has very small initial stability (low GM) a large heel angle will be required to generate a restoring moment equal to the mean wave-induced heeling moment. But, as the equilibrium heel angle increases, the force imbalance on the hulls increases, causing the heel angle to increase still further. In the worst case the heel angle will continue to increase until the pontoon breaks the water surface, a condition that was observed in the test.

Tests performed with a wave direction of 165 degrees still showed a mean tilt angle, demonstrating that the effect is still observed with slight changes in vessel heading. In fact for the effect to disappear, the heading has to change sufficiently for the roll component of the wave to overwhelm the vertical wave drift force imbalance. These results were verified by the diffraction analysis. The effect will also disappear if the initial stability is sufficient to limit the initial heel angle and prevent the vertical wave drift force imbalance from increasing. Because the difference between vertical forces on pontoons for a given angle of heel is greater the closer the pontoons are to the water surface, the initial stability required to eliminate the effect will be less as the pontoon submergence (draft) increases.

**Operational Aspects**

**Deepwater Developments**

The majority of today's deep-water developments are located in the Gulf of Mexico, Brazil, and West Africa. These are all areas with moderate environments characterized by much lower wave heights than are found in areas subject to harsh environments such as the North Sea and Eastern Canada. In these moderate environments semi-submersibles show sufficient airgap and acceptable motion characteristics for stability columns with less height than their harsh-environment cousins. This reduction in height of the stability columns significantly reduces the capital costs, but also influences the stability of the semi-submersible.

A deep-water semi-submersible must have high deck load capacity because deepwater developments tend to be far offshore, where re-supply is expensive. Efficient compartmentation and placement of down flooding points allows the high deck loads required to perform in deep water to be carried with relatively low initial stability (small GM values). Small initial stability values increase angular motion natural periods and may reduce pitch and roll motions in waves. A shortcoming of low initial stability at operating draft is that it may be necessary to reduce variable deck load at survival draft because the stability rules intact 100 knot wind criteria becomes more onerous than the damage criteria.

**Roll motions in short Waves and Currents**

The low frequency roll motions seen during model tests have also been observed during actual operations in low period waves combined with current. With the vessel in head seas, larger than expected roll motions have been observed. The period of the roll motions, approximately 40 sec, is the same as the vessel natural roll period which confirms that these roll motions are due to low frequency forcing. It should be noted that to date, when the low frequency roll has been experienced, the magnitude of the roll motion has not been significant enough to hinder drill floor operations. It should be noted that due to the model tests discussed above, design changes were made to the hull prior to construction that significantly reduced these motions although not completely removing them.

To manage the vessel when this does occur, the crew found that by changing the vessel heading by 30-45 degrees the roll motion can be completely removed without the addition of any pitch motion. This supports the conclusions arrived at during the model tests discussed above, in that the vertical wave drift forces acting upon the pontoons are sufficient to cause low frequency roll motions in head seas.

Also of significance is the fact that the vessel draft affects the low frequency roll phenomenon, although typically a heading change is all that has been required, and draft changes have never been utilized to remove this phenomenon.

**Crane Operations**

The deepwater developments on which 5th generation semi-submersibles are working involve major logistical plans to ensure that the well construction process continues 24hrs per day. These logistical plans involve handling items of various shapes and weights, ranging
from a 0.5 tonne work basket to 75 tonne subsea production trees or manifolds. Typically cranes installed on these semi-submersibles have increased in size to accommodate these larger payloads, which significantly helps the operator simplify planning issues and reduce costs associated with hiring alternate vessels to complete the infrastructure that the drilling vessel is constructing.

The cranes used to handle these large payloads have long and heavy booms. Figure 8 shows how the vessel angle of heel/trim varies for the same load and distance moved with GM. It can be seen at GM values less than 2 or 3m the angle of heel/trim will be much greater than at GMs larger than this. The load and distance is representative of a 150 tonne static load rated crane which has a 50 tonne boom with center of gravity approximately 30m from the crane pedestal.

Therefore, depending on the cranes selected for the vessel, the GM limit imposed for operations should consider that the weight of the boom alone could cause the vessel to heel/trim unacceptably.

**Rig Floor Pipe Handling**

As discussed above, a consequence of installing larger cranes is that they come with much larger booms. The downside to this is that when handling small loads with the crane, which represent 95% of all lifts the crane will make, the rig will have a greater tendency to roll/pitch due to the crane movement when compared to a less capable crane which could equally perform these small lifts. This can impact drill floor operations where pipe being passed through the rotary needs to be kept centrally located. Due to the crane movement, which is typically going on 24hrs per day, the rig will have a tendency to heel/trim which results in the drillers needing to be more careful when setting the slips (Figure 9) on pipe to ensure the pipe is not resting on one side which may cause the slips to not set properly. The consequence of not setting the slips correctly can be dropping pipe in the hole that must be avoided. In addition with the pipe not centrally located it can drag on the side of the slips causing premature wear on the dies that grip the pipe.

**Vessel Ballasting**

Without the drilling guide the rig is required to trim the vessel frequently to try to keep the pipe centrally located, something that is not practical in day-to-day operations.

Typically semi-submersibles do not routinely transfer ballast between pontoons. Although this is not a class rule it has been adopted as a best practice within the industry from lessons learned from previous incidents. Having the ability to routinely transfer ballast between pontoons would make keeping the vessel level much simpler though, since you would not need to be concerned with keeping a constant vessel draft as the ballast remains onboard throughout the process.

Therefore to level the vessel you must take on ballast in one pontoon and remove ballast from the other, while at the same time keeping the vessel draft constant. Performing this task constantly on a vessel with low initial stability is not ideal. Therefore a semi-submersible should be designed with adequate stability to prevent this requirement as existing stability rules will not prevent this from occurring.

**The VDL trade-off**

The key requirement for these rigs is a high variable deck load (VDL) due to the type of deepwater development work that they are being scheduled for as discussed above.

The conflict when deciding the vessel VDL is that the aim of the vessel designer is to maximize VDL while ensuring the vessel meets all Class stability requirements. Vessel designers have been able to meet all Class stability requirements with GM>0m being the
limiting factor, and as can be seen from Figure 8 proves impractical, which has been the case since the first floating vessels were designed. The trade-off for the designers and owners asks the question, “What is an acceptable range of stability (GM) values to use when there are no Class requirements governing?”

The vessel’s designers must address the answer to this question, but the vessel owners must be very aware of the decisions behind the VDL limit imposed on the design. Recently the methods outlined in this paper have been used to limit the VDL on newly-built semi-submersible designs where practical considerations have governed over Class requirements.

Conclusions

In short waves and high currents, the vertical lift loads on the pontoons of the semi-submersibles result in roll motions in head seas. These roll motions occur mainly around the natural frequency of the semi-submersible. For smaller GM values the period increases and the roll damping becomes more quadratic. This process results in an increase of the standard deviation of roll for decreasing GM.

The methods and considerations outlined in this paper should aid designers and owners in determining how and when to limit the VDL of the vessel in order to provide a safe and practical working platform.

References

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