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Complementary Roll Motion Control of a Moored FPSO in Deepwater West Africa

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ABSTRACT: *This work presents complementary control of Roll excitationby bilge keels in order to increase the global performance of BONGA FPSO in West African deep waters. Five (5) different sizes and configurations of bilge keels defined by the drag diameters were attached to the FPSO and the roll response analyzed using time domain technique in ORCAFLEX. The decay simulation for 60s and sustained dynamic simulation for 1800s were carried out for the sizes using the 100yr return period data of FPSO location, its principal dimensions and roll motion characteristics. Results showed that the roll amplitude decayed linearly with increase in the bilge keel drag diameter for the same environmental and hull parameters for both cases. An average roll amplitude reduction of about 2.06^o signifying 38.3% was obtained for the largest bilge keel with a drag diameter of 2.5m when compared to the bare hull or base case (i.e. 0.0 m drag diameter). For the bilge keel with a drag diameter of 1.5m, a 1.42^o reduction in roll amplitude was observed; which is an improvement of about 0.865^o for an increase of 1m in drag diameter from 0.5m. However, a marginal reduction of roll amplitude analysis reveals that at a predicted drag diameter of about 4.6m, the percentage gain in roll reduction varnishes to zero showing that there is always an optimum size of bilge keel for targeted roll response reduction. Evidently however, the observed reductions are enough to cause significant increase in the global performance of the FPSO.*

KEYWORDS: *Roll, motion, bilge-keel, stabilization, FPSO,deep-water, Orcaflex*

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I. INTRODUCTION

Floating vessels responds to six degrees of freedom of motion that affect their stable operation. While three of these namely, Surge, Sway and Heave are translational in nature, the remaining three namely, Roll, Pitch and Yaw are rotational in nature. Amongst the rotational motions, the Roll Motion which acts about the longitudinal axis has been seen to be the most critical motion to consider in stability analysis as the ship is more likely to capsize in the Transverse direction.

FPSOs have become preferred units for operations in deep and ultra-deep waters because of their relative advantages. However, due to the severity of its operating environment adequate station keeping system to guarantee safe operation is cautionary in order to guarantee safety of operation. Dynamic Positioning Systems as well as other Mooring Systems have been developed to keep the FPSO in a position. However, because of dynamic amplification of environmental forces, sometimes not envisaged during the design stage, global performance is hampered leading to unwarranted downtimes during operation.

For the FPSO vessel, the roll motion response under various internally and externally generated loads such as Riser flows, mooring lines tension, cargo tanks sloshing, wind, wave and current is of utmost importance with regards to safety.

Presently, the BONGA FPSO uses a u-tank roll stabilization system but with suspected insufficient roll stabilization for the unit which sometimes weathervanes to a beam sea direction, thus exposing the unit to greater roll motion. This necessitated the quest for a complementary system to mitigate the attendant risk.

Roll motion stabilization has been extensively studied and there exists a rich library of results. (1)used the CFD method based on a harmonic excited roll motion (HERM) technique to compute the roll motion and the roll damping moment of a container-ship's model in different conditions. (2) in their work, utilized a scale model and a hybrid-passive truncated experimental method for mooring lines and risers and showed thatit was possible to investigate the global response of an FPSO including the dynamics of mooring lines and risers, in the context of prevailing environmental conditions, for field development in a specific deep water location in the Gulf of Mexico. Indeed, several other works such as the followings:-(3), (4), (5), (6), (7), (8), (9), (10), (11), (12), (13), (14), (15), (16), (17), (18), (19), (20), (21), (22), (23), (24), (25), etcare available in published literatures. Interestingly, one common denominator to all of these researches has been the quest to achieve reduced vessel responses resulting from excitation forces and true to the fact, they each had tremendous results.

In this work however, the bilge keel stabilization device, because of the simplicity in its installation, operation, efficiency and low CAPEX,shall be used to reduce the roll motion of a FPSO vessel currently operating in the West African Gulf of Guinea with a view to increasing the global performance. The analysis will employ real design and operational parameters of the FPSO and Metocean parameters of the Gulf of Guinea to evaluate the roll amplitude reduction capabilities of different sizes (defined by drag diameters) of bilge keel.

II. MATERIALS AND METHODS

Principal Hull Dimensions for BONGA FPSO

The typical hull dimensions considered are:

- Length Between Perpendiculars: 295m
- Breadth (Moulded): 58m
- Depth (Moulded): 32m
- Design Draft (Moulded): 23.43m
- Scantling Draft (Moulded): 23.95m

Proposed Bilge keel sizes for roll reduction

Table 1: Proposed Bilge keel sizes

S/no	Bilge keel sizes in Diameter (D) [m]
1	0
2	0.5
3	1
4	1.5
5	2.0
6	2.5

Environmental data:

The BONGA location is shown in figure 2.1 below. Environmental Data for the location are typical of the Gulf of Guinea because the Bonga FPSO is located 120 kilometers (75 mi) southwest of the Niger Delta in the Gulf of Guineaat an average water depth of 1,000 meters (3,300 ft). The environment is typical of having benign wind, wave and current conditions. Vessels in this region are not prone to harsh weather conditions as the region is generally considered as benign.

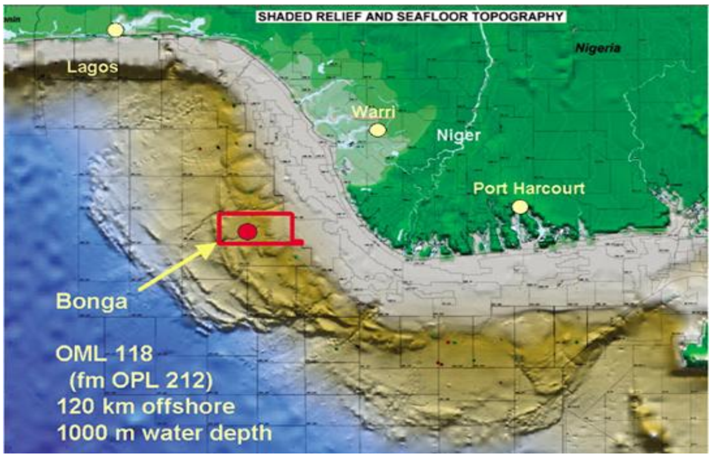


Fig 1: Shaded Relief and Seafloor Topography Showing OML 118

The FPSO Model will be analyzed for extreme values of the Metocean parameters in the Gulf of Guinea. Some of these parameters include wind speed, significant wave heights, peak and zero-up-crossing periods, wave frequencies, etc.These will be simulated in a direction, 90-degrees of the Hull's Global orientation, representing intense beam-sea conditions. The key environmental data considered are those of the wave and wind as shown below:

The wave data are;

– Significant wave height (H_s) = 5.0m;
– Zero crossing period (T_z) = 10s;
– Wave direction: 90^o;
– Fm = 0.0715Hz;
– Peak period (T_p) =13.9935 s

The wind data are;

– Wind Speed 10m/s;
– Mean wind direction 90^o;
– Air density: 0.0013 T/M^3;
– Kinematic viscosity: 15.000E-6 m^2/s;
– Analysis will be done for a 100-year return period.

Hydrodynamic Simulation procedure of Bilge Keels using Orcaflex 10.3C

The bare-hull, risers, and mooring chains for the Bonga FPSO were used in the hydrodynamic analysis to optimize global performance of the system using Orcaflex. The bilge keels in the hydrodynamic tool operate on the Morrison Elements. Morison elements are collections of cylinders which attract hydrodynamic drag forces. Morison elements represented by the Bilge Keels were rigidly attached to the FPSO referred to as the owner of the elements (Bilge Keels).

The functionality is identical for both types of owner.

- Element type

The element typeholds the drag data and the drawing data for the element.

- Position and orientation

The position defines the location of end A of the element, relative to the owner's origin and with respect to the owner axes. The element's z -axis is defined by the azimuth and declination angles. The z -axis points from end A towards end B along the axis of the cylinder. The x -axis and y -axis are the normal directions of the cylinder, defined by the gamma angle.

- Length, **L**

The length of the element.

- Number of segments, **N**

The element is discretized into N sub-elements of length l =L/N.

- Morison element type data

The Morison element type data define the hydrodynamic properties of the Morison elements. Multiple element types can be defined, with data specified on the Morison element type form.

- Drag diameters

The normal drag diameter, d_n, and the axial drag diameter, d_a. If d_a is set to' ∞' then the value of d_n is used.

- Drag coefficients

The drag coefficients CD_x, CD_y and CD_z, with respect to the element's local axes.

The axial coefficient, CD_z, is constant, while the normal coefficients, CD_x and CD_y, may take, independently, the form of a fixed constant value or a value that varies with Reynolds number

The normal coefficients often take the same value; this can be indicated conveniently by setting '∞' for CD_y, to mean 'same as CD_x '.

The fluid velocity and surface elevation used in the drag load calculation take account of the wave calculation method and disturbance vessel (if any) specified by the owner. For elements attached to a vessel, which do not support a choice of wave calculation method or disturbance vessel, the wave kinematics are always calculated at the element's instantaneous position (exact) in the undisturbed sea state.

Principal Dimensions and Drag Parameters for FPSO Modelling

The following principal dimensions are considered for the modelling of the unit; the length of the element, L; Number of segments, N; The element is discretized into N sub-elements of length (l = L/N).

Drag diameters; The normal drag diameter, d_n, and the axial drag diameter, d_a.

Drag coefficients; The drag coefficients CD_x, CD_y and CD_z, with respect to the element's local axes.

The procedure includes the tasks below

- Each element is discretized into N sub-elements. The drag force is then calculated separately for each sub-element and applied at the center of the sub-element.
- The drag force is calculated using the crossflow principle. That is, the fluid velocity V_r relative to the sub-element is split into its components V_n and V_z normal and parallel to the element Z-axis.
- The drag force normal to the element Z-axis is then determined by V_n and its X - and Y -components V_x, V_y; the drag force parallel to the element Z-axis is determined by V_z.
- The drag force vector, $\mathbf{F}_D$, for a sub-element is given by:

$$F_{Dx} = \frac{1}{2} P_w \rho D_n l C_{Dx} V_x |V_n| \qquad 1$$

$$F_{Dy} = \frac{1}{2} P_w \rho D_n l C_{Dy} V_y |V_n| \qquad 2$$

$$F_{Dz} = \frac{1}{2} P_w \rho \pi D_a l C_{Dz} V_z |V_z| \qquad 3$$

Where the following parameters are defined accordingly:

ρ- fluid density

Pw - proportion wet, calculated using the same method as used for lines, with the sub-element circumference determined by Dn

F_D - (F_{Dx}, F_{Dy}, F_{Dz}) in element local coordinates

To identify the significant parameter, the parameters above were used in series of simulations and analysis of the FPSO Model for different loading and environmental conditions. See Orcaflex Model of FPSO's Bare-Hull in figure 2below.

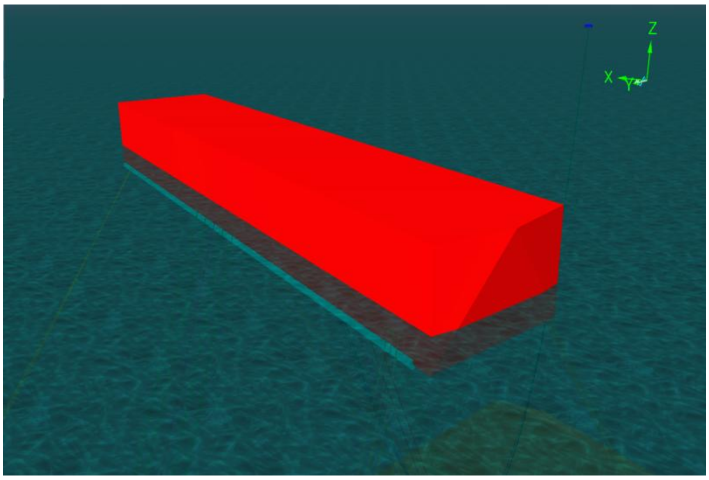


Fig. 2: Orcaflex Model of FPSO's Bare-Hull.

Application of Bilge Keels in Roll Motion Reduction

Fig.3 below shows the FPSO model in the Orcaflex domain, and the dimension of the identified significant parameter used to represent the bilge keel which was modeled as a Morrison element.

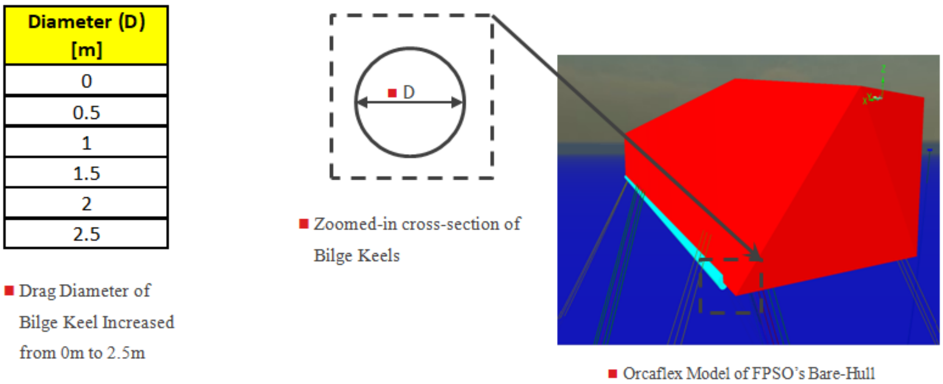


Fig.3: Modifying drag diameter of the hull's Orcaflex model

To achieve significant roll motion reduction, a variation was done in the drag diameter. After trying out different diameters during the analysis, a workable range of 0 to 2.5 meters of the bilge keel was selected. The Metocean conditions remained the same throughout the analysis. Vessel parameters were also not altered throughout the analysis. The analysis was done in the frequency domain and results obtained accordingly.In the hydrodynamic analysis tool – Orcaflex, external loads were seen to act at beam-sea which includes the points on the FPSO where external loads incident on them produce roll motion and hence the analysis can be done studying the response motions and taking note of the reductions in roll as the drag diameter of the bilge keels on the FPSO's Orcaflex model changed from 0 to 2.5metres. It's important to note here that the drag diameter was used to model the bilge keel on the hull and that the circular nature of the bilge keels is for software analysis purposes as in real life practice, it will be represented by steel plates instead.

III. RESULTS AND DISCUSSIONS

Decay study of FPSO roll motion

The first was the excitation of the unit by the wave and the unit's roll motion allowed to decay for 60s. Here, six configurations of the hull were used with a base case signifying a zero-bilge hull form. This zero-bilge case was done to obtain a base case for the simulation in order to identify accurately changes resulting from other bilge keel-modified hulls. The base case was selected for same model parameters, but with bilge keel drag diameter, 0 m. Fig.4 below shows the plot of the roll amplitude against time for all the hull configurations. A virtual inspection of the plots indicate that even though the decay trends may be similar there are however, marked positive reductions in the roll amplitude along the line of increasing bilge keel size from the base case.

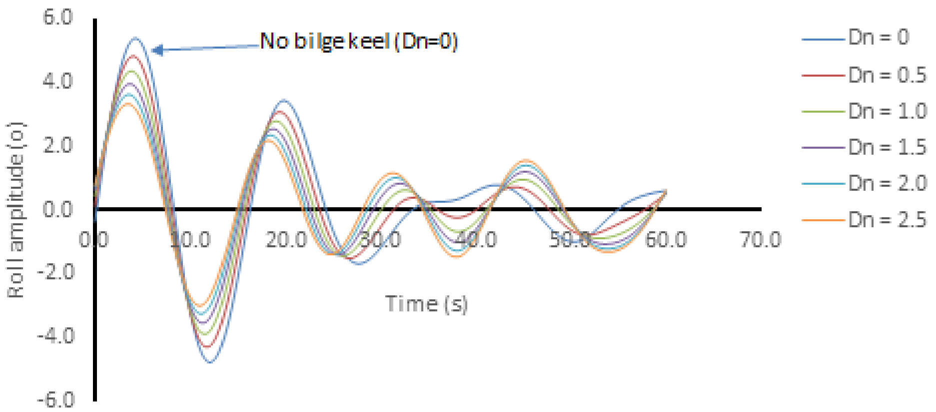


Fig 4: Roll amplitude time history showing extent of roll decay for all the hull configurations

Statistical Analysis of Time History Data From Simulation

A statistical analysis on the time history data resulting from the simulation performed is presented on Table 2 below to show the impact of the modified hulls relative to the base case.

Table 2 Descriptive statistics showing impact of bilge keels on hulls for 60s decay

	Dn (m)	0	0.5	1	1.5	2	2.5
Roll amplitude (°)	max	5.370	4.810	4.342	3.945	3.607	3.313
	min	-4.764	-4.287	-3.883	-3.538	-3.246	-2.991
	sd	2.116	1.882	1.723	1.609	1.528	1.464
	mean	0.232	0.186	0.150	0.121	0.099	0.082
	range	10.134	9.098	8.225	7.484	6.853	6.305
	sig.value	8.465	7.530	6.891	6.437	6.110	5.856
	Roll reduction						
	max roll	0.000	0.559	1.027	1.424	1.763	2.056
	mean roll	0.000	0.046	0.082	0.110	0.132	0.150
	range	0.000	1.036	1.909	2.650	3.281	3.829
	sig value	0.000	0.935	1.574	2.027	2.354	2.608

Graphical plots of Table properties of Table 2 above as seen from figures 5 to 8 below show reduction in roll amplitude due to the addition of bilge keels to the hull. From these figures, it is evident that reduction in roll is positively related to the drag diameter.

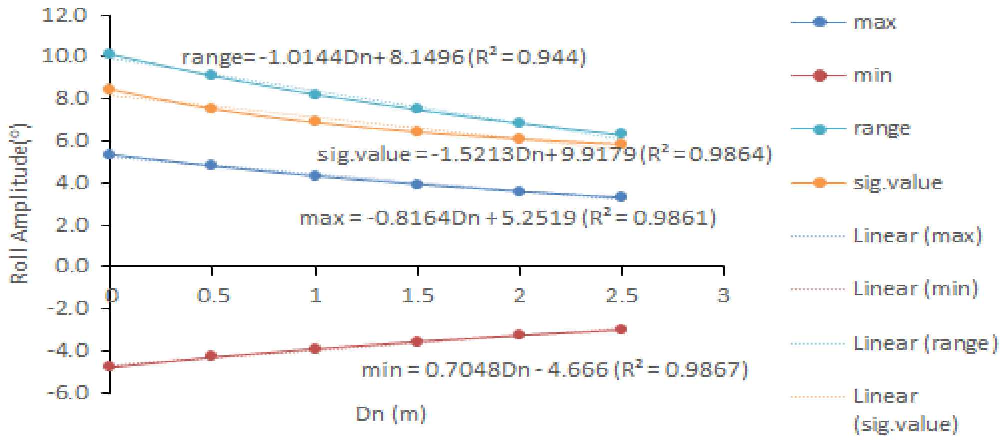


Fig. 5: Impact of bilge keel (drag diameter) on Roll amplitude (max, min, range and significant value parameters) for decay simulation

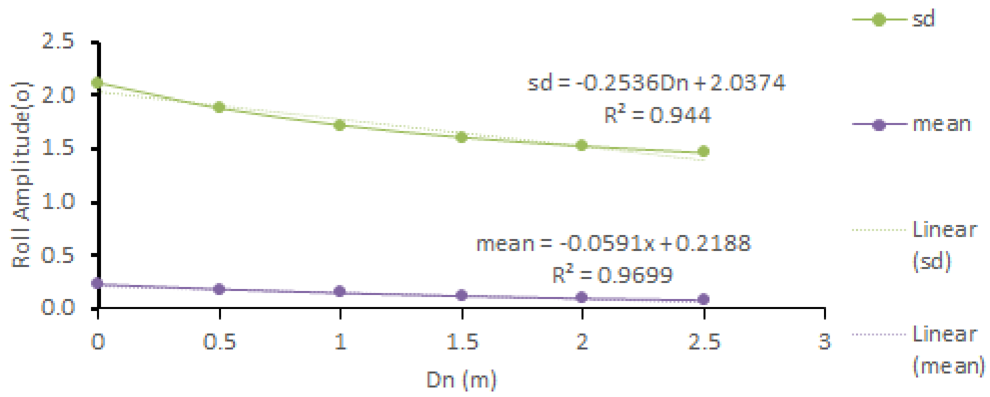
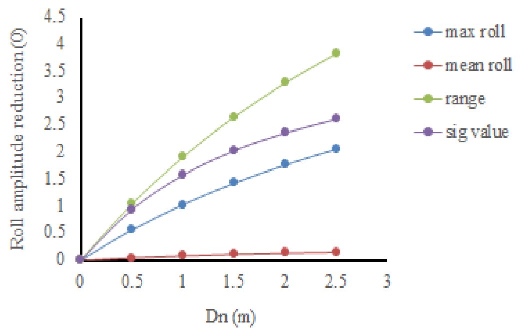


Fig.6: Impact of bilge keel (drag diameter) on Roll amplitude standard deviation and mean



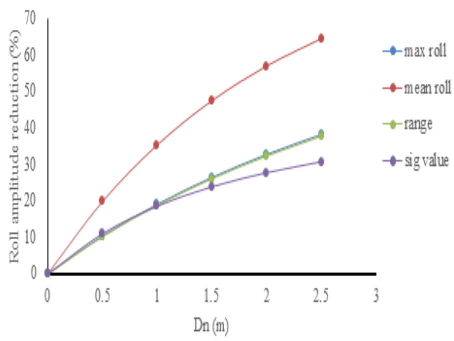


Fig 7: Roll Reduction vs bilge keel size (absolute values) Fig.8: % Roll Reduction vs bilge keel size

From the statistical parameters analyzed, the base case has a max or peak roll of about 5.4° and the corresponding minimum standard deviation (sd), the mean value, range and the approximated significant roll amplitude were observed to be -4.764°, 2.116°, 0.232°, 10.134° and 8.465° respectively. The second simulation case represents a given bilge keel size run at a drag diameter of 0.5m and that produced a roll of 4.8° with a recorded percentage reduction of 10.41% which translates to a 0.559 ° drop in the roll amplitude. Similar percentage reduction of 10.22%, 11.05% and 19.86% were observed in the mean, range and sig. values respectively. With an increased bilge size of Dn =1.0m compared to the base case, a positive gain in peak roll of 4.34 ° indicating a 1.27 ° or 19.14% reduction was achieved. A remarkable marginal increase of 8.73% was observed compared to the bilge keel size Dn=0.5m. Similar variations were also observed in the other specified parameters. The fourth simulation case was run at a drag diameter of 1.5 m and that produced a peak roll of 3.95°, i.e. a significant reduction of 1.42 ° and 26.53%. The fifth (Dn=2m) and sixth (Dn=2.5m) bilge keel sizes simulation cases produced peak roll amplitudes/reduction/% reductions of 3.61 °/1.76 ° /32.8% and 3.31

^{o}/2.06/38.29% respectively. Apparently, the sixth bilge keel with larger diameter gave the highest reduction of peak roll amplitude as can be seen however, the marginal gain in % reduction reduces as the bilge keel size increases. This of course is an indication that, though larger bilge keels may produce the best reduction of peak roll within the contest of this simulation, it does not necessarily mean that they are selected as an optimum size for utilization. See table 3 below for the estimated marginal gains across the parameters.

Table 3: Marginal gains of statistical parameters

Marginal Gain in statistical parameters						
Dn	0.0	0.5	1.0	1.5	2.0	2.5
Max		-0.5592	-0.4683	-0.3969	-0.3383	-0.2935
Min		0.4768	0.4046	0.3447	0.2924	0.2545
Sd		-0.2337	-0.1597	-0.1134	-0.0817	-0.0635
Mean		-0.046	-0.036	-0.0281	-0.0221	-0.0174
Range		-1.036	-0.8729	-0.7415	-0.6306	-0.548
sig.value		-0.9349	-0.6387	-0.4535	-0.3269	-0.254
Roll reduction marginal gains						
max roll	0.0	0.5592	0.4683	0.3969	0.3383	0.2935
mean roll	0.0	0.046	0.036	0.0281	0.0221	0.0174
Range	0.0	1.036	0.8729	0.7415	0.6306	0.548
sig value	0.0	0.9349	0.6387	0.4535	0.3269	0.254
Roll reduction (%) marginal gains						
max roll	0.0	10.4136	8.7212	7.3914	6.2999	5.4656
mean roll	0.0	19.8581	15.5363	12.1413	9.5262	7.5279
Range	0.0	10.2232	8.6132	7.3175	6.2231	5.4077
sig value	0.0	11.0449	7.546	5.3579	3.8621	3.0012

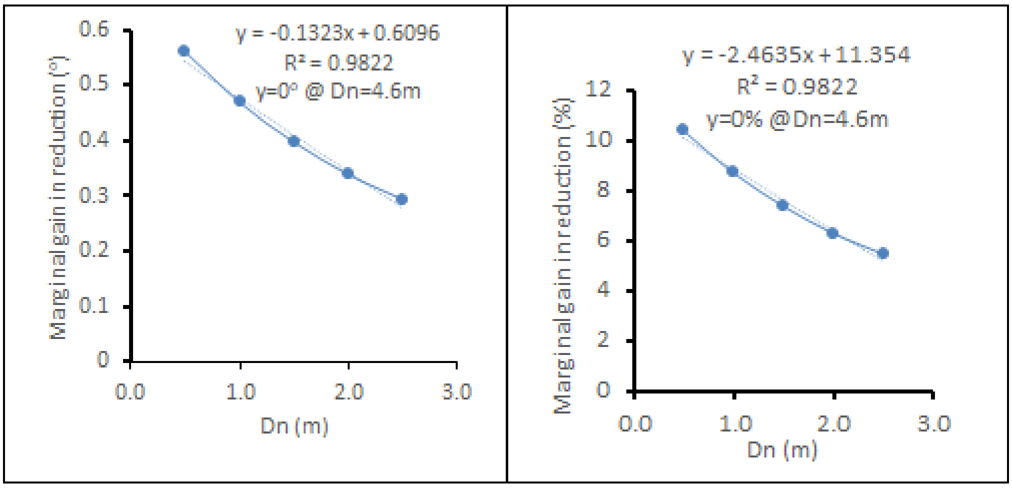


Fig 9: Marginal gain in peak(max) roll amplitude reduction vs bilge keel size (a)in ^{o} (b) in %

From the linear fit in figure 9 above, it is evident that there is a diminishing gain in the roll reduction resulting from increase in bilge keel size. Further investigation reveals a significant point of zero gain at Dn=4.6m after which, there is the likelihood of the bilge keel resulting in a negative marginal gain. This value of Dn=4.6m can be used as an optimum value if it is not too big for the hull of the FPSO.

Summarily, from peak roll angles of 5.4^o, the FPSO's Model roll motion response angle reduced significantly to 3.31^o. This significant change justifies the effectiveness of bilge keels in roll motion reduction of the FPSO. The Roll of the FPSO's model was reduced by 2.06^o over a 2.5m increase in drag diameter. This is a very significant difference in the Gulf of Guinea where the sea state is benign as compared to other regions in the world. This analysis helps to further advice the hang-off and attachment angles of the risers, mooring chains and umbilicals. It has been seen from various deep-water projects and assets that an improved global response motion of the hull of a floating structure will improve the corresponding motions of other systems attached to it.

Impact of Bilge keel on sustained dynamics of unit

The effect of the hull modification due to bilge keel was investigated by allowing the excitation for a period of 30mins and a sample of the time history for the base case (no bilge keel, Dn=0) and the hull with bilge keel (Dn=2.0m) cases are presented in fig.10 below.

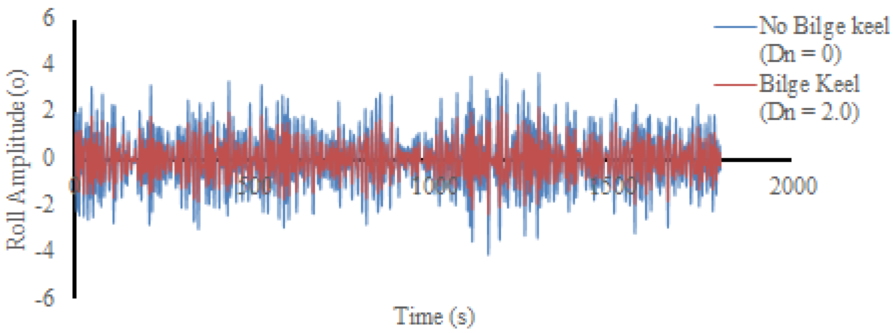


Fig.10: Roll amplitude time history for 30mins simulation showing effect of bilge keel

Table 5 Descriptive statistics of 30mins roll amplitude time history

Roll Amplitude (°)	Dn (m)	0	0.5	1	1.5	2
	max	3.102	2.705	2.377	2.092	1.852
	min	-2.587	-2.234	-1.936	-1.693	-1.507
	sd	1.451	1.261	1.103	0.969	0.855
	mean	-0.039	-0.034	-0.030	-0.026	-0.023
	range	5.689	4.940	4.313	3.785	3.359
	sig.value	5.806	5.044	4.410	3.876	3.420
	Roll reduction (°)					
	max roll	0.000	0.397	0.725	1.010	1.250
	mean roll	0.000	0.005	0.009	0.013	0.016
	range	0.000	0.749	1.376	1.904	2.330
	sig value	0.000	0.761	1.395	1.929	2.386
	Roll reduction (%)					
	max roll	0.000	12.788	23.370	32.548	40.297
	mean roll	0.000	12.676	23.037	32.319	40.067
	range	0.000	13.172	24.181	33.464	40.958
	sig value	0.000	13.111	24.034	33.234	41.095

The plots of figures 11 to 13indicate similar trend to what was observed from the 60s decay simulation. However, over a bilge diameter size of 2.0m, the reduction in max roll amplitude recorded was about 1.25^{o} against 1.76^{o} observed for the decay simulation at the same size of bilge keel. The percentage reduction, which stands as the maximum reduction was 40.30% when the value of 1.85^{o} was compared to the base case of 3.10^{o}. This reduction is about 2.0% difference when compared to the decay simulation which recorded a 38.3% reduction. Similar percentage reduction of 40.07%, 40.96% and 41.10% were observed as the roll reduction from the mean roll, range and significant values respectively. The pattern is repeated for the other bilge keel sizes as shown in figure 13.

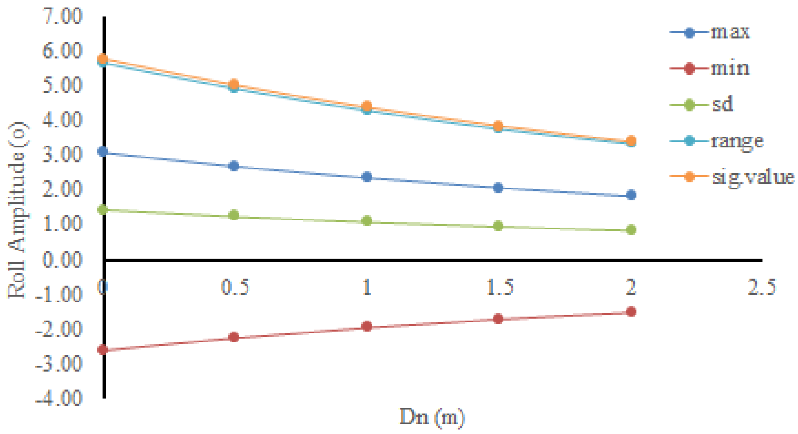
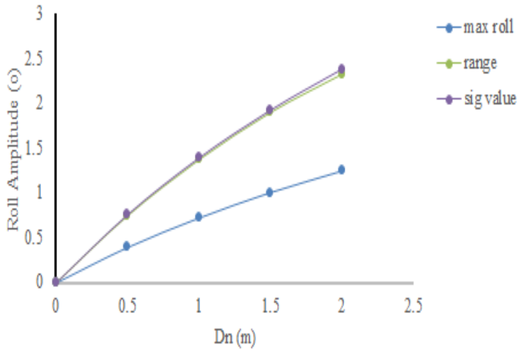


Figure 11: Impact of bilge keel (drag diameter) on Roll amplitude (max, min, range, sd and significant value parameters) for dynamic run.



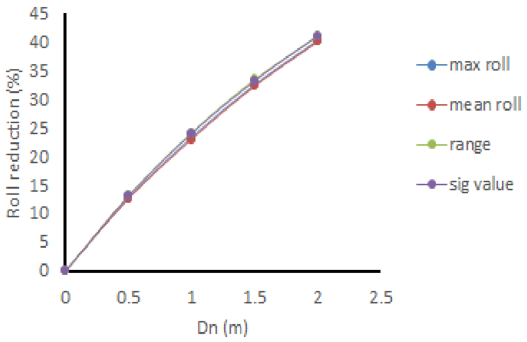


Fig. 12: Roll Reduction dynamic run(absolute values) **Fig. 13:** % Roll Reduction dynamic run

IV. CONCLUSION

The stable operation of the FPSO unit due to its roll behaviour is assessed using the rate at which the roll amplitude is affected due to the presence of the bilge keel. The roll motion of Bonga FPSO was analysed using Orcaflex 10.3c Version. Various roll motion stabilization systems were studied, and the bilge Keels were selected for the Analysis. Bilge keels work on the principle of Morison elements in Orcaflex and the model equation was analysed highlighting all key parameters in the Model. The drag diameter is representative of the width of the Bilge keel. The drag diameter in the model equation was identified as a key component having a significant impact on the roll motion of the FPSO Model. The base case for roll was obtained. In course of the analysis it was seen that increasing the drag diameter, reduces the roll motion of the FPSO model, hence improving the Global performance of the FPSO. A significant reduction in roll motion of 2.06^{o} was obtained from the analysis of a 60s roll amplitude time history or the decay simulation. Global hull performance was improved. This was also observed from the 30mins sustained dynamics for the 1.25^{o} for the maximum recorded roll amplitude. A 40% reduction of roll amplitude was recorded within the sizes tested computationally. Similar trends were also observed for the other statistical parameters used for the data analysis. It is therefore concluded that the addition of a bilge keel will enhance the seakeeping capability of the facility.

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