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Optimal Design of FPSO Vessels

Ezebuchi Akandu [a,*]

[a)]*Department of Marine Engineering, Rivers State University, Port Harcourt, Nigeria*

*Corresponding author: akandu.ezebuchi@ust.edu.ng

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ABSTRACT

The evaluation of principal dimensions of a Floating Production, Storage and Offloading (FPSO) system is one of the most critical tasks at the initial design stage of the vessel. It is therefore important to get this right from the onset. This paper presents a simple method of determining the optimal principal dimensions of FPSO vessels of any specified oil storage capacity. An Optimal Design Programme (OPTIMAP) has therefore been developed to analyze and compare the various responses of floating production vessels with the aim of selecting the best possible design to ensure not only a reduction in cost of construction, but also to maintain a safe operation and overall optimal performance of the vessel with regards to her dynamic responses in deep sea waves.

KEY WORDS: *FPSO, Principal Dimensions, Optimal Design, Relative Goodness.*
.

NOMENCLATURE

B	Beam or breadth of vessel
C_f	Conversion factor from bbl to m^3 ($C_f = 6.28981077$)
C_n	Cubic number
D	Vessel molded depth or height
∇	Displacement (in m^3) of vessel (FPSO)
e	Maximum allowable green water exceedance
E_i	Green water exceedance levels for $i = 1\ to\ n$ vessels
E_s	Oil storage efficiency
FPSO	Floating Production, Storage and Offloading vessel
g	Acceleration due to gravity
GM_T	Transverse metacentric height
κ_i	Green water factors
L	Vessel length between perpendiculars
OPTIMAP	Optimal design programme
ProGreen	Green water analysis programme
RAO_s	Response amplitude operators
RGM	Relative goodness method
R	bales' seakeeping rank
R_i	Most probable relative motion (between the bow and the wave) for each of the vessels
S_c	Required oil storage capacity
T	Draught
WavBen	Bending moment program
w_j	A set of weighting factors, $j = 1\ to\ m$ responses
x_b	Length-breadth ratio
y_d	Dreadth-depth ratio
$\zeta_i^{(j)}$	Responses for $i = 1\ to\ n$ vessels
z_m	Draught to depth ratio
Ω_i	Relative goodness values or ranks

1.0 INTRODUCTION

The problem of optimization can be described as the process of minimizing the objective response function(s), in order to have the best performance, in relation to some predetermined geometric and functional constraints. The objective function is the user-defined sea-keeping related response characteristics such as the RAOs (the maxima of RAOs may be used), the root-mean-square values, or the most probable maximum values (in situation where extreme value determination may be of paramount importance). These response characteristics have been found to be a function of the principal dimensions and/or the underwater form of the vessel.

Various choices of optimization variables in a number of approaches and their related problems have been discussed by Hearn et al. [1]. Furthermore, Hooke and Jeeves' [2] direct search

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method has been found to work well in solving optimization problems with solution evaluated by nonlinear programming techniques.

Generally, these methods have several limitations when they are applied to sea-keeping problems partly due to the challenges of obtaining suitable objective functions for such analyses. In view of these challenges, Bales [3] proposed a different objective function for minimization. It is known as the Bales sea-keeping Rank which is given by:

$$R = \sum_{j=1}^{m} w_j r_j \quad (1)$$

In this case, the designer determines a set of responses r_i and their various weighting factors, w_j, where $j = 1\ to\ m$ responses included in the objective functions. The response weighting factors are values of judgement which the designer must make on the basis of the mission requirements which he is attempting to satisfy [3]. They represent the relative importance of the various response characteristics being analyzed.

2.0 THEORETICAL FORMULATION

2.1 Objective Function

Since there are indeed multiple response characteristics that may be required to be minimized, the objective functions have to be expressed in terms of their overall measure of their goodness (or acceptance) and the geometric constraints for a required constant storage capacity (which is directly related to the vessel's cubic number). It is possible to quantify the relative goodness (a measure of its desirable dynamic performance). It is defined as the sum of the weighted inverse proportionalities of the dynamic response characteristics of the FPSO vessel. In other words, for a vessel to remain safe and efficiently productive in challenging, extreme meteorological and oceanic conditions, it is desirable to minimize its responses especially the heave and pitch motions. It may be desirable to include other wave effects that influence the cost of construction and maintenance at the initial design stage. The wave bending moment and the effects of green water for instance may be considered and minimized as well, at the design stage. A vessel with lower wave bending moment, for instance, will require less amount of steel and hence lower cost to construct. Therefore, in this analysis, the effects of wave bending moment will be included as a form of response characteristic in the objective function that requires minimization.

The structure of the optimization problem comprises the following descriptors:

(i) Design geometric variables
(ii) Geometric and functional constraints
(iii) Objective functions (as a function of (i) and (ii))
(iv) Relative goodness (as a function of (i), (ii) and (iii)).

2.2 Geometric Variables and Constraints

Since the size and arrangement influence the cost of construction of the vessel, it is important to consider the factors affecting them [4]. These include provision of sufficient: (i) Oil storage capacity, (ii) Deck area, and (iii) Displacement and ballast capacity.

The required oil storage capacity, S_c, which is the required maximum volume of crude oil to be safely stored in the storage tanks of the vessel, must be known and made compatible with the production rate and offloading arrangements. It is ideal to relate this to a constant overall volume known as the cubic number of the vessel using a desirable oil storage efficiency. The Oil Storage Efficiency, E_s , is the ratio of the required oil storage capacity to the overall cubic volume provided by the hull. The required storage capacity, in barrels of oil, is given by:

$$S_c = C_f \times E_s \times C_n \quad (2)$$

$C_n = L \times B \times D = Cubic\ number$
$L = Length\ between\ perpendiculars$
$B = Breadth$
$D = Depth\ moulded$
C_f = Conversion factor
($C_f = 6.28981077$; That is: $1m^3 = 6.28981077bbl$).

Having found the cubic number in terms of the oil storage capacity and the storage efficiency, it becomes relatively easier and rational to express the two remaining factors (provision of sufficient deck area, displacement and ballast capacity) which also influence the size as a function of the design geometric variables, length-breadth (x_b), and breadth-depth (y_d) ratios. With this in mind, the geometric constraints are therefore given by:

$$x_{b_{min}} \le x_b \le x_{b_{max}} \quad (3)$$

$$y_{d_{min}} \le y_d \le y_{d_{max}} \quad (4)$$

These geometric constraints can be transformed in terms of the vessel lengths as given below:

$$L_{min} \le L \le L_{max} \quad (5)$$

Where: $L_{min} = \left(x_{b_{min}}{}^2 \times y_{d_{min}} \times \frac{S_c}{C_f \times E_s}\right)^{1/3}$

$$L_{max} = \left(x_{b_{max}}{}^2 \times y_{d_{max}} \times \frac{S_c}{C_f \times E_s}\right)^{1/3}$$

Consider length-breadth ratio ranging from 4.5 to 5.8 and breadth-depth ratios ranging from 1.4 to 2.4, both with incremental steps of 0.1. This yields one hundred and fifty four (154) different designs of FPSO with minimum and maximum length of about 250 and 354m for 2 million barrels oil storage capacity FPSOs.

The major task here is to select the vessel (from say, the total of 154 FPSO vessels in the above-mentioned case study) which will have the best performance in terms of various relevant dynamic responses such as the heave, pitch, bending moment and/or the effects of green water due to operation in extreme wave condition. It may not be enough to select a vessel with only just the minimum heave, pitch, bending moment, or the green water exceedance level as there may not be such vessel with all

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the responses minimized at the same time. The proposed relative goodness method (RGM) is a reliable way of analyzing the performances of these vessels and then selecting the overall best based on the general design requirements and functional constraints. The general preliminary design constraints are as follow [5]:

(i) The storage capacity must be capable of taking the output during the average interval of shuttle tanker calls.
(ii) The transverse metacentric height, GM_T, must be around 3 or more, in the fully-loaded condition.
(iii) The natural rolling period must be greater than 12 seconds. A good design usually has the natural motion periods longer than the peak period of the spectrum which is exceeded for less than 2% of the time and low heave forces and pitch moments at all shorter periods.
(iv) In order to ensure that a better motion response is achieved, the zero force frequencies for heave and pitch must be spread out as much as possible.
(v) The ratio L/D must be less than 13 (from structural point of view).
(vi) The underdeck volume should not exceed 1.8 times the displacement. This implies that:
(vii) $D/T \leq 1.8$, i.e. $T \geq 0.56D$.
(viii)This enables the vessel to accommodate the segregated ballast and the produced water storage capacity.
(ix) The required external surface areas should be as small as possible, which implies low values L/B and L/D ratios.
(x) The induced motions should not exceed the levels within which the separators have been designed to operate. Conventional separators have been designed to cope with the following levels of motion: Angular motions, 0 to 7.5^o; linear motions, 0 to 0.25g; periods, 3 to 15s.
(xi) In extreme wave condition, effects of green water should be reduced by minimizing freeboard exceedance [6, 7].

2.3 Optimal Design Using Proposed Relative Goodness Method (RGM)

Let $i = 1\ to\ n$ different FPSO vessels to be analysed, $j = 1\ to\ m$ response characteristics, $\zeta_i^{(j)}$ being considered with weighting factors, w_j. Then, the relative goodness, Ω_i, of each of the vessels, which is a very good measure of the sea-keeping rank (especially in comparism with that of the Bales') is given by:

$$\Omega_i = \kappa_i \sum_{j=1}^{m} \left[\frac{w_j \ \zeta_{min}^{(j)}}{\zeta_i^{(j)}} \right] \tag{6}$$

Where $\kappa_i = 1$ when the green water exceedance, E_i, is less or equal to the maximum allowable level, e, above the top of the freeboard.

$$\kappa_i = 1 - \frac{E_i - e}{E_{max}}; \ when \ E_i > e \tag{7}$$

The overall best of all the vessels under investigation is the vessel with the maximum value of the relative goodness, Ω_i.

The green water exceedance levels have been evaluated by Akandu [7]:

$$E_i = R_i - (1 - z_m)(x_{bi} \times y_{di}{}^2)^{-\frac{1}{3}} \left(\frac{S_c}{C_f \times E_s} \right)^{\frac{1}{3}} \tag{8}$$

Where $z_m = \nabla / C_n \approx 0.65$, and R_i is the most probable relative motion in m for each of the vessels.

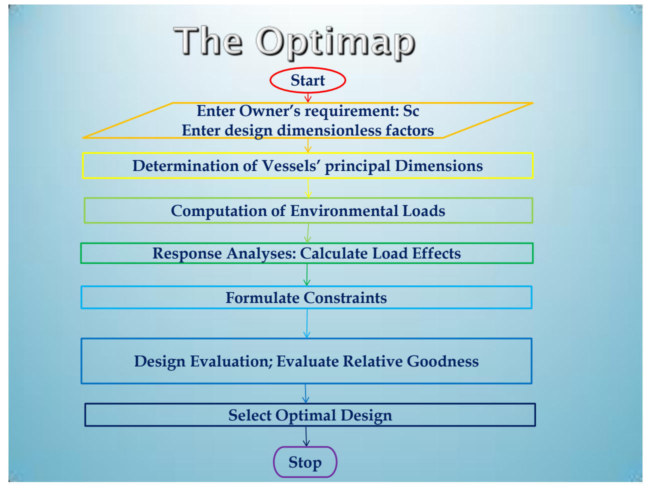

Figure 1: Optimal design Programme Flowchart

3.0 RESULTS AND DISCUSSIONS

154 2-million barrels oil storage capacity FPSOs have been designed and analyzed with the most probable maximum responses evaluated. The analysis is aimed at not only predicting these responses but also selecting best which has the overall optimum dynamic response. Some vessel operators may require the one with the optimal heave, others might be delighted to have vessel that will have the problem of green water onboard solved. Also, lower bending moment at amidships will mean lesser steel material and therefore, lower cost of construction. All these factors have been considered with special emphasis on the green water constraint which requires that the maximum green water exceedance level should not exceed 2m. This programme which is called OPTIMAP allows users to input the allowable green water exceedance. It also allows users to choose the sea state in terms of significate wave height and zero up-crossing period. In this case, 16.5m and 17.5s respectively have been used

The overall optimal designs for up to 0, 1, and 2m permissible green water exceedance levels have been obtained as:

Table 1: The overall optimal principal dimensions for 0, 1, and 2m permissible green water exceedance levels

e	L	B	D	T
0	256.9	54.7	39.0	25.4
1	274.8	52.8	37.7	24.5
2	295.6	51.0	36.4	23.7

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See Table 2 and Table 3 for more details.

Most of the vessels with lower breadth-depth ratios (1.4 to 1.8) have sufficiently high freeboard necessary to overcome green water issues as also indicated by their high relative goodness values (See Annex A). For any given breadth-depth ratio, the peak of the graph of the relative goodness gives the optimal point. See figures 2-9.

4.0 CONCLUSIONS AND RECOMMENDATIONS

From the analysis, the following may be concluded:

(i) The relative goodness values of the FPSO vessels are good measures of the sea-keeping ranks of the vessels as they highlight the applicability or operability of such vessels.
(ii) The programme which has been developed using this relative goodness method is known as OPTIMAP and it incorporates the principal dimensions, motion, bending moment and green water analyses programme (ProGreen). Please, see [7-9]. This computer aided design tool (OPTIMAP) effectively evaluates and selects the best design by finding the overall optimal response with respect to the geometric and functional constraints for any given sea state.
(iii) The susceptibility to green water problem of the vessel has been accounted for or minimized using the above optimal design programme (OPTIMAP).
(iv) Most of the vessels with lower breadth-depth ratios (1.4 to 1.8) have sufficiently high freeboard necessary to overcome green water issues as also indicated by their high relative goodness values (See Annex A).
(v) The cost of construction of the vessel is apparently reduced since the vessel with relatively lower bending moment which requires lesser steel materials is selected.
(vi) For any given breadth-depth ratio, the peak of the graph of the relative goodness gives the optimal point.
(vii) It is recommended that the root-mean-square and the peak values of the response amplitude operators should be applied for re-computation of the optimal design points. In this particular analysis, the most probable maxima were evaluated and applied in the programme.

ACKNOWLEDGEMENTS

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ANNEX A:
THE RELATIVE GOODNESS OR OPTIMAP NUMBER OF 154 2-MILLION BARREL STORAGE CAPACITY VESSELS

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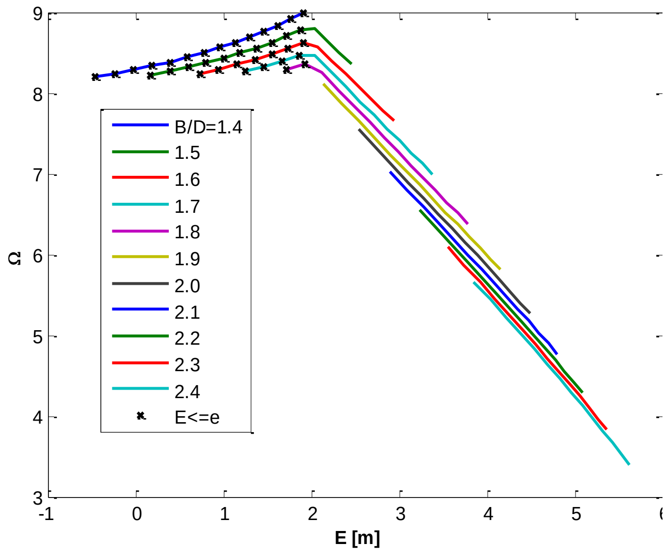

Figure 2: The variation of relative goodness, Ω, with the most probable maximum green water exceedance for specified breadth-depth ratios

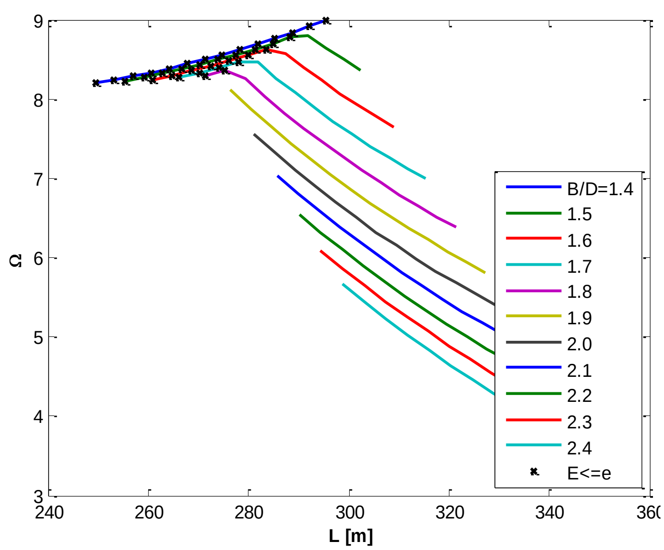

Figure 3: The relative goodness versus, Ω, the Length for specified breadth-depth ratios

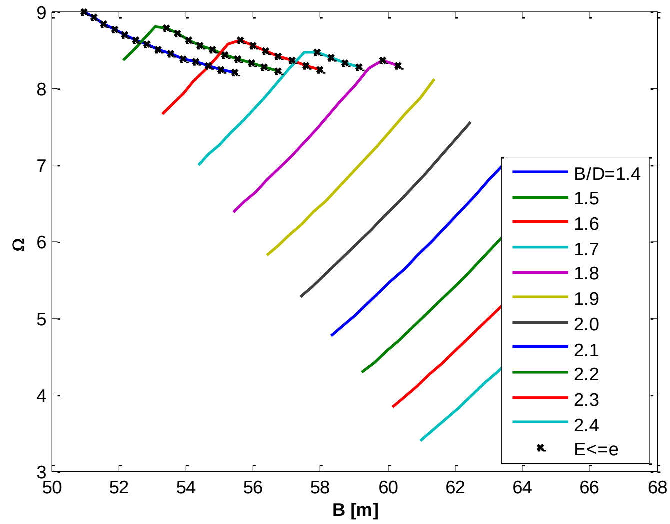

Figure 4: The graphs of relative goodness, Ω, versus the Breadth for specified breadth-depth ratios

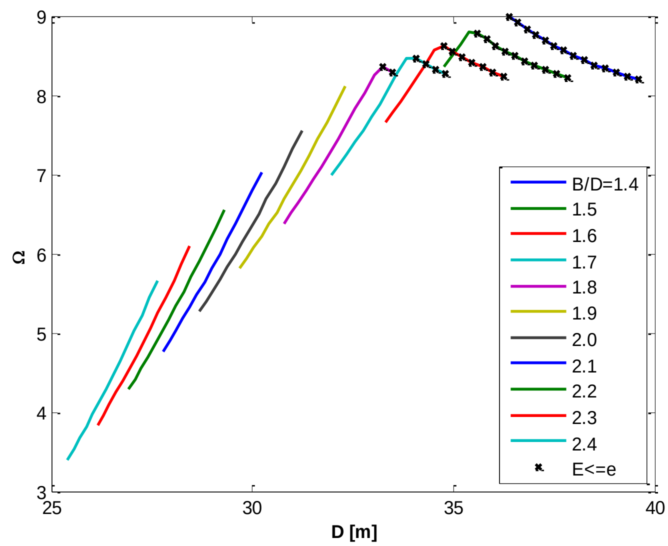

Figure 5: The relative goodness, Ω, versus the Depth for specified breadth-depth ratios

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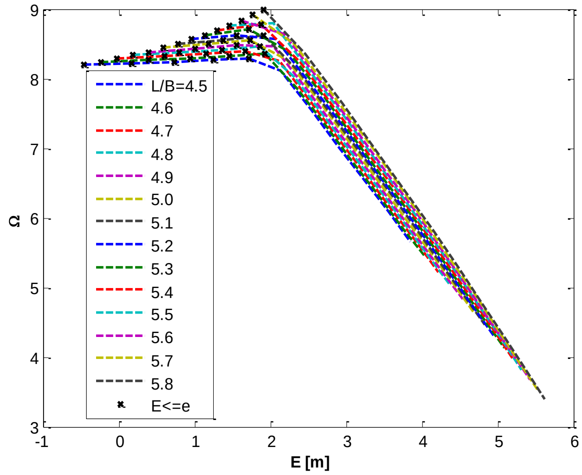

Figure 6: The variation of relative goodness with the most probable maximum green water exceedance for specified length-breadth ratios

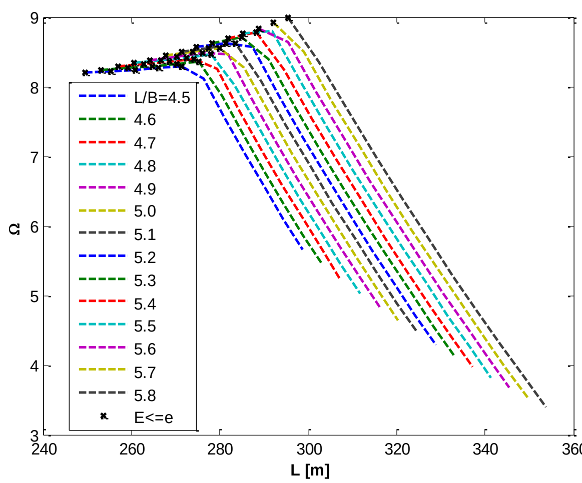

Figure 7: The relative goodness versus the Length for specified length-breadth ratios

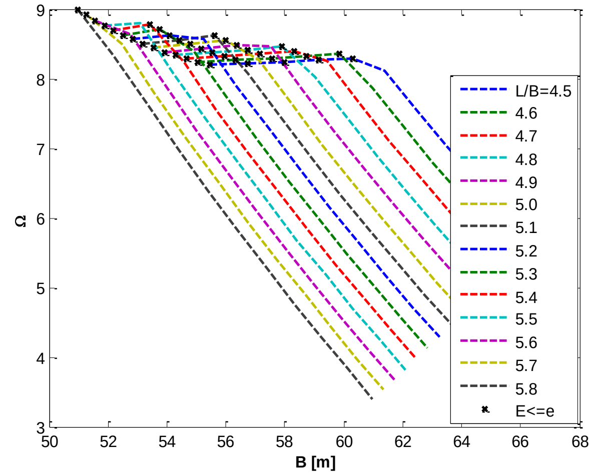

Figure 8: The graphs of relative goodness versus the Breadth for specified length-breadth ratios

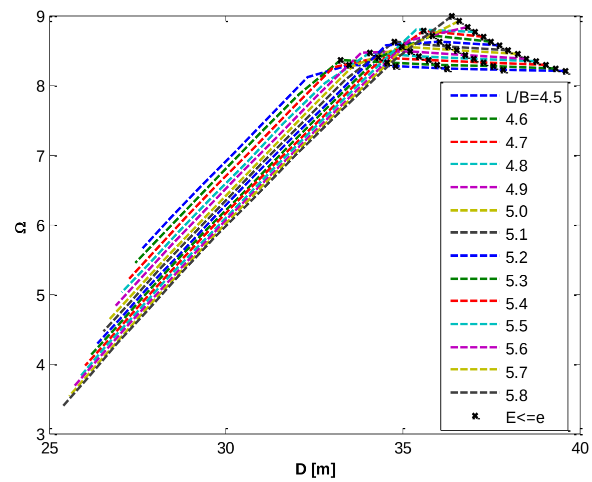

Figure 9: The relative goodness versus the Depth for specified length-breadth ratios

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Table 2: The Responses and the Relative Goodness Values of 2-Million Barrel Storage Capacity FPSO Vessels that satisfied the specified allowable Green Water exceedance of 2m (above the main deck)

L/B	B/D	L [m]	B [m]	D [m]	T [m]	ζ_3 [m]	ζ_5 [deg]	BM [GNm]	Ω
4.5	1.4	249.5586	55.4575	39.6125	25.7481	13.1114	8.5615	9.3011	8.2021
4.5	1.5	255.3643	56.7476	37.8318	24.5906	12.8534	8.3465	9.4938	8.2207
4.5	1.6	260.9175	57.9817	36.2385	23.555	12.6191	8.1452	9.6736	8.2432
4.5	1.7	266.2438	59.1653	34.8031	22.622	12.4052	7.9567	9.8438	8.268
4.5	1.8	271.3651	60.3034	33.5019	21.7762	12.209	7.78	10.0072	8.2939
4.6	1.4	253.2422	55.0526	39.3233	25.5602	12.9801	8.4801	9.3109	8.2419
4.6	1.5	259.1336	56.3334	37.5556	24.4111	12.7232	8.2627	9.4909	8.2676
4.6	1.6	264.7687	57.5584	35.974	23.3831	12.4901	8.0595	9.6582	8.2968
4.6	1.7	270.1737	58.7334	34.5491	22.4569	12.2775	7.8694	9.8163	8.3277
4.6	1.8	275.3706	59.8632	33.2573	21.6173	12.0826	7.6915	9.9681	8.3591
4.7	1.4	256.8992	54.6594	39.0424	25.3776	12.8509	8.3975	9.312	8.2858
4.7	1.5	262.8757	55.931	37.2873	24.2368	12.5951	8.1779	9.479	8.3187
4.7	1.6	268.5922	57.1473	35.717	23.2161	12.3634	7.9729	9.6337	8.3544
4.7	1.7	274.0752	58.3139	34.3023	22.2965	12.1523	7.7814	9.7797	8.3913
4.8	1.4	260.5303	54.2772	38.7694	25.2001	12.7237	8.3139	9.3047	8.3336
4.8	1.5	266.5913	55.5399	37.0266	24.0673	12.4694	8.0922	9.4586	8.3737
4.8	1.6	272.3886	56.7476	35.4673	23.0537	12.2392	7.8855	9.6007	8.4159
4.8	1.7	277.9491	57.9061	34.0624	22.1406	12.0296	7.6927	9.7348	8.4586
4.9	1.4	264.1364	53.9054	38.5038	25.0275	12.5987	8.2294	9.2894	8.3853
4.9	1.5	270.2813	55.1594	36.773	23.9024	12.3459	8.0057	9.4301	8.4324
4.9	1.6	276.1588	56.3589	35.2243	22.8958	12.1174	7.7975	9.5596	8.4811
5	1.4	267.7179	53.5436	38.2454	24.8595	12.4758	8.1442	9.2664	8.4406
5	1.5	273.9462	54.7892	36.5262	23.742	12.2248	7.9186	9.3939	8.4948
5	1.6	279.9034	55.9807	34.9879	22.7421	11.9981	7.709	9.5111	8.5497
5.1	1.4	271.2757	53.1913	37.9938	24.696	12.3553	8.0583	9.236	8.4995
5.1	1.5	277.5867	54.4288	36.2858	23.5858	12.1062	7.831	9.3504	8.5607
5.1	1.6	283.6231	55.6124	34.7577	22.5925	11.8813	7.6201	9.4557	8.6217
5.2	1.4	274.8103	52.8481	37.7487	24.5366	12.2371	7.9718	9.1986	8.5619
5.2	1.5	281.2035	54.0776	36.0517	23.4336	11.99	7.743	9.3004	8.6298
5.3	1.4	278.3223	52.5136	37.5097	24.3813	12.1212	7.885	9.1548	8.6274
5.3	1.5	284.7973	53.7353	35.8236	23.2853	11.8762	7.6548	9.2442	8.702
5.4	1.4	281.8123	52.1875	37.2768	24.2299	12.0077	7.7978	9.105	8.6961
5.4	1.5	288.3684	53.4016	35.601	23.1407	11.765	7.5664	9.1827	8.7771
5.5	1.4	285.2808	51.8692	37.0495	24.0821	11.8966	7.7105	9.0498	8.7677
5.6	1.4	288.7284	51.5586	36.8276	23.9379	11.7879	7.6231	8.9898	8.8419

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5.7	1.4	292.1555	51.2553	36.611	23.7971	11.6816	7.5357	8.9255	8.9187
5.8	1.4	295.5626	50.9591	36.3993	23.6596	11.5777	7.4485	8.8577	8.9977

Table 3: The Responses and the Relative Goodness Values of 2-Million Barrel Storage Capacity FPSO Vessels that satisfied the specified allowable Green Water exceedance of 0m (above the main deck)

L/B	B/D	L [m]	B [m]	D [m]	T [m]	ζ_3 [m]	ζ_5 [deg]	BM [GNm]	Ω
4.5	1.4	249.5586	55.4575	39.6125	25.7481	13.1114	8.5615	9.3011	8.2021
4.6	1.4	253.2422	55.0526	39.3233	25.5602	12.9801	8.4801	9.3109	8.2419
4.7	1.4	256.8992	54.6594	39.0424	25.3776	12.8509	8.3975	9.312	8.2858

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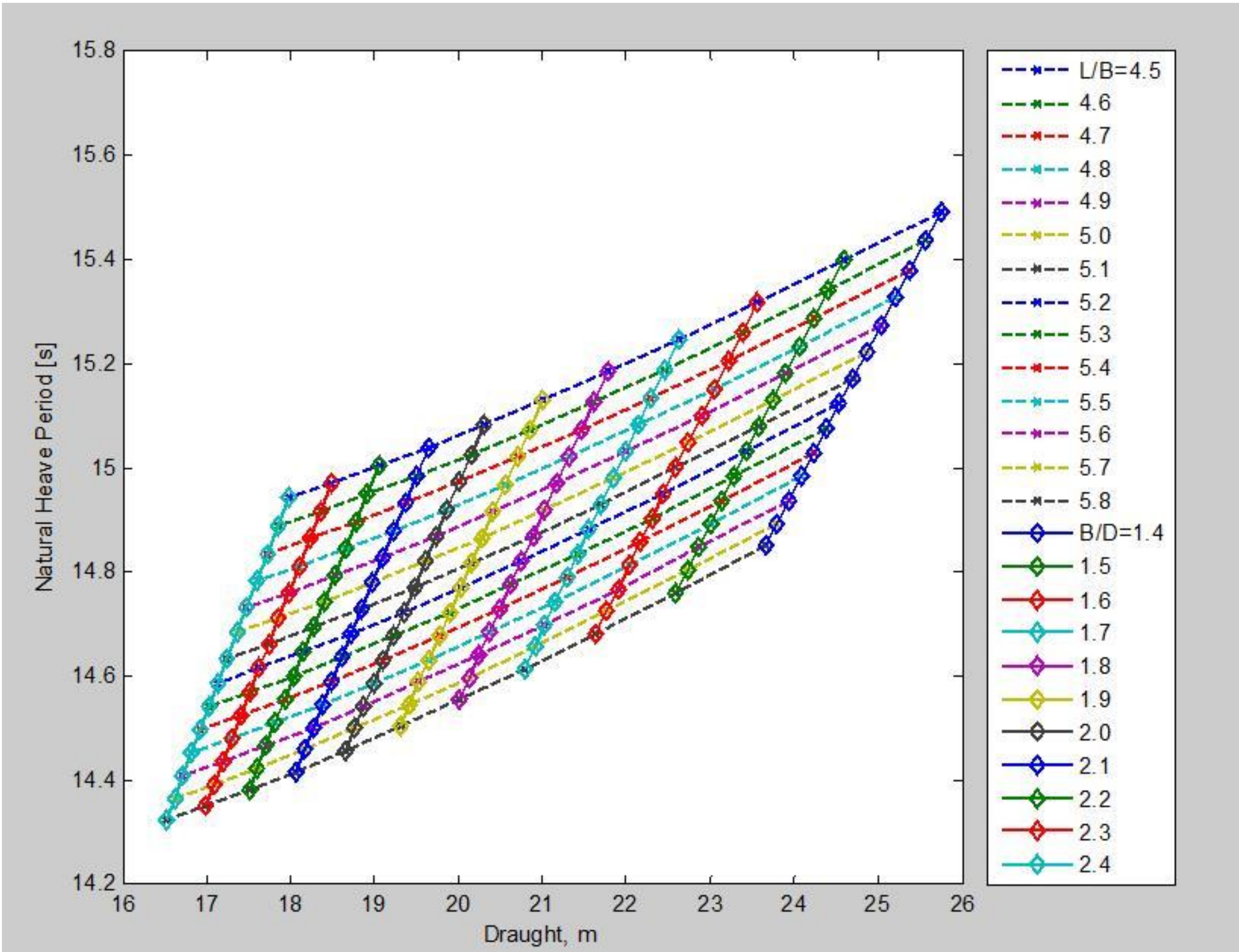

Figure 10: Variations of Natural Heave or Pitch Period with Draught

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