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ClubStead Preliminary Analysis:
Hydrostatic and Hydrodynamic Analysis

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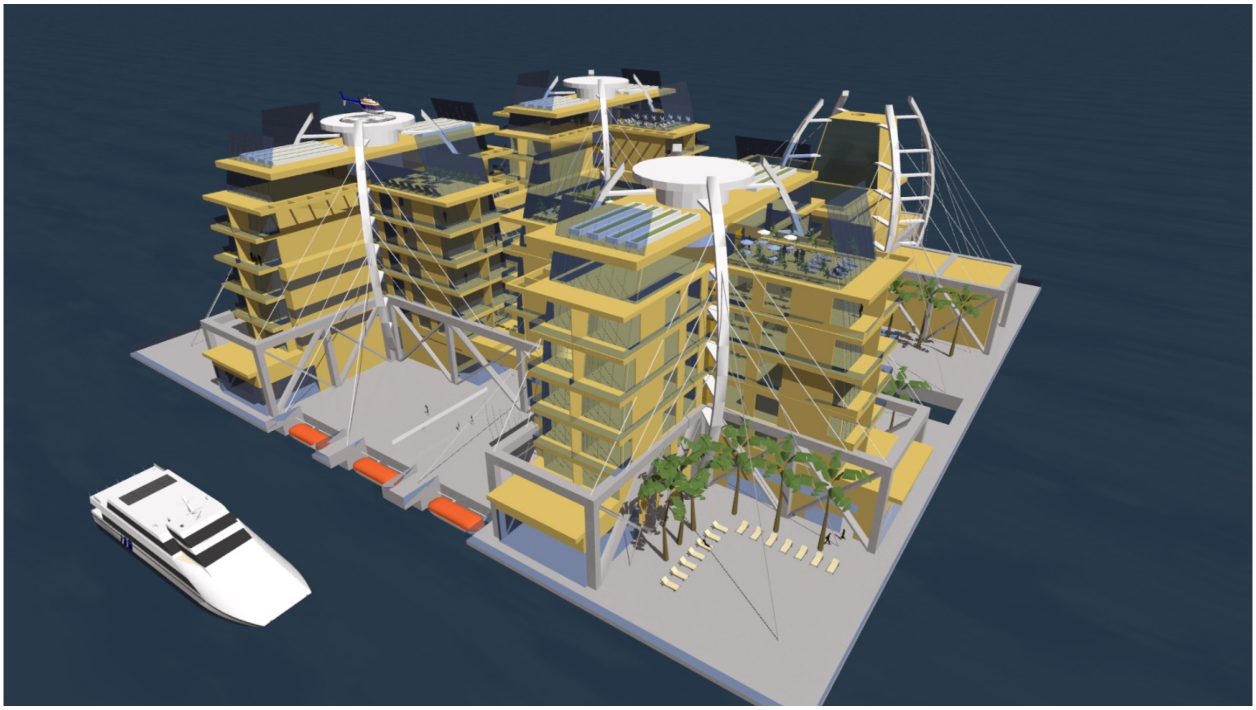
ClubStead Preliminary Analysis: Hydrostatic and Hydrodynamic Behavior



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1. Summary and Conclusions

The present hydrodynamic analysis aims at verifying the design feasibility of a ClubStead located off the coast of San Diego, CA. Design criteria focus on the survivability of the ClubStead in harsh environmental conditions. This document also investigates the operational performance of the floater regarding passenger comfort.
The ClubStead is a floating housing facility with a displacement of 20,900st. Its main hydrostatic and hydrodynamic characteristics are summarized in Table 1.

Table 1: Main Characteristics of the ClubStead

Length	400	ft
Breadth	400	ft
Draft	75	ft
Airgap	40	ft
Displacement	20908	st
including ballast	5233	st
Center of Gravity above keel KG	94.5	ft
Metacentric Height GM	13.7	ft
Heave Natural Period	17.1	sec

Following API recommendations, the ClubStead is designed to survive a 100-year storm at its intended location off the coast of San Diego, CA. 3-hour simulations of the 1 year, 10-year and 100-year storms are carried out with the hydrodynamic software tool TimeFloat. The minimum clearance between the deck and the wave crest is 5.83ft. The maximum pitch and roll angle is 5.45 degrees.

Overall, the ClubStead behavior meets the survivability criteria.

Empirical data is necessary to ascertain parameters used in the numerical model presented herein. Numerical modeling of 1st order wave motions is highly accurate, but drag coefficients and air-gap are best determined with model testing.

The comfort aboard the ClubStead is characterized by the standard deviation of the vertical acceleration, according to International Standard ISO 2631. The standard states that, at typical wave peak frequencies, a majority of the passengers is seasick after being exposed to a vertical acceleration RMS of $0.25 m/s^2$ for 8 consecutive hours. Such levels of vertical accelerations occur on the ClubStead less than 5% of the time (Table 2).

Table 2: Probability of Exceedence of Vertical Acceleration RMS

	Probability of Occurrence (%) of Vertical Acceleration RMS > than	
Position	0.1 m/s2	**0.25m/s2**
Center of deck	43	1.3
Extremity of Deck 1	65	1.5
Extremity of Deck 2	72	5.4
Top of Tower 1	48	1.3
Top of Tower 2	48	1.3

Compared to the performance of a ship-shape vessel, the ClubStead is more comfortable throughout the entire deck. Given the frequent occurrence of long period waves on site, passenger comfort could be even further improved by increasing the heave natural period. This result should be taken into account in further design stages.

2. Introduction

The ClubStead is a four legged platform with a payload of 7,700st, which includes buildings and open architectural areas on the 400 by 400 ft deck. It is designed to remain all year long off the coast of San Diego, CA. To avoid lease and permitting issues, the platform is not moored, but dynamically positioned (DP) on site. The DP system consists of a propulsion system with thrusters located at the bottom of the columns and is used to maintain loose position.
The current design was updated from the previous version, which had a 5000st payload, to take into account the latest architectural work and the sizing of the primary deck structure described in a joint structural report. The global sizing of the platform has been adjusted to meet design requirements.

This report focuses on the hydrodynamic performance of the ClubStead. The design basis is defined with respect to the intended use of the ClubStead. As a living facility, the platform must ensure a comfortable environment to its passengers in all operational sea-states. It must also be able to survive extreme weather in the open oceans.
Both types of requirements are considered herein. The behavior of the ClubStead in harsh and operational conditions is investigated using hydrodynamic programs WAMIT and TimeFloat. The sensitivity of the results to numerical parameters is examined.

The hydrodynamic analysis leads to an assessment of the ClubStead behavior at its intended location, off the coast of San Diego. Additional remarks point out possible design optimization to minimize the heave and pitch related motions.

3. Global Description and Frame of Reference

Table 3 highlights the main dimensions of the platform. The air-gap is the distance between the mean waterline and the lowest deck elements. In the case of the ClubStead, it is the distance to the bottom of the buoyancy module. The buoyancy module is 10ft high and the lower living spaces are located above the buoyancy module as illustrated in Figure 1. The suspended areas are accessible at the bottom level of the buildings. The beams that support these areas extend 3ft below at most. Depending on the location on the deck, the distance between the deck and the mean waterline is either 40ft, under the buoyancy module or 47ft, under the beams supporting the suspended surfaces.

Table 3: Global Dimensions

COLUMNS			
	Number of columns	**4**	
	Column diameter	41	ft
	Footing Diameter	76	ft
	Footing Height	20	ft
	Draft	75	ft
	Airgap (distance to bottom of buoyancy module)	40	ft
DECK			
	Distance column center to column center	200	ft
	Length of horizontal extension beyond column	100	ft
	Width of a building	50	ft

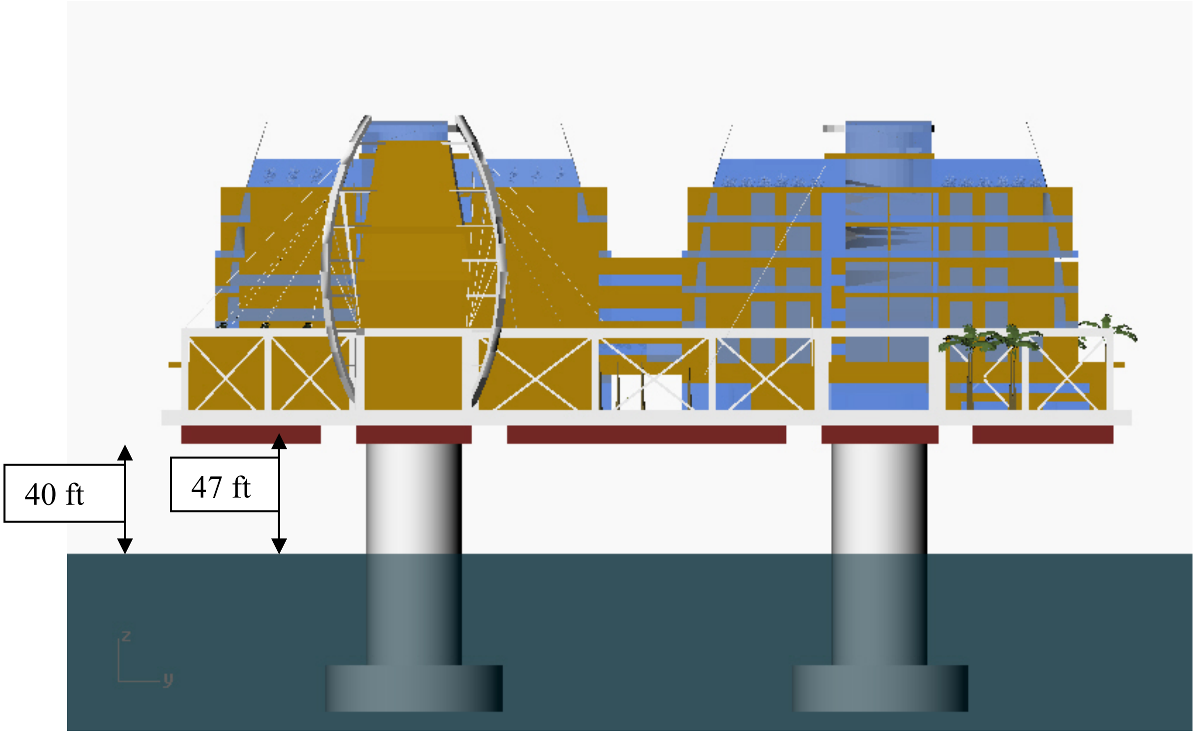

Figure 1: Side View of the ClubStead Platform

The mass properties of the ClubStead are summarized in Table 4.

Table 4: Mass Properties

Description		unit
Total Weight	20,908	st
CG (position of center of gravity w.r.t. the waterline)	19.5	ft
Radius of Gyration Rx	87.5	ft
Radius of Gyration Ry	87.5	ft
Radius of Gyration Rz	112.4	ft

The mean referential Cxyz centered between the columns and described in Figure 2 is used in the hydrodynamic analysis. Wave and wind directions are defined anti-clockwise from the x-axis. Due to the symmetry of the structure, only 0 and 45 degree heading wind and waves are studied in the numerical analysis.

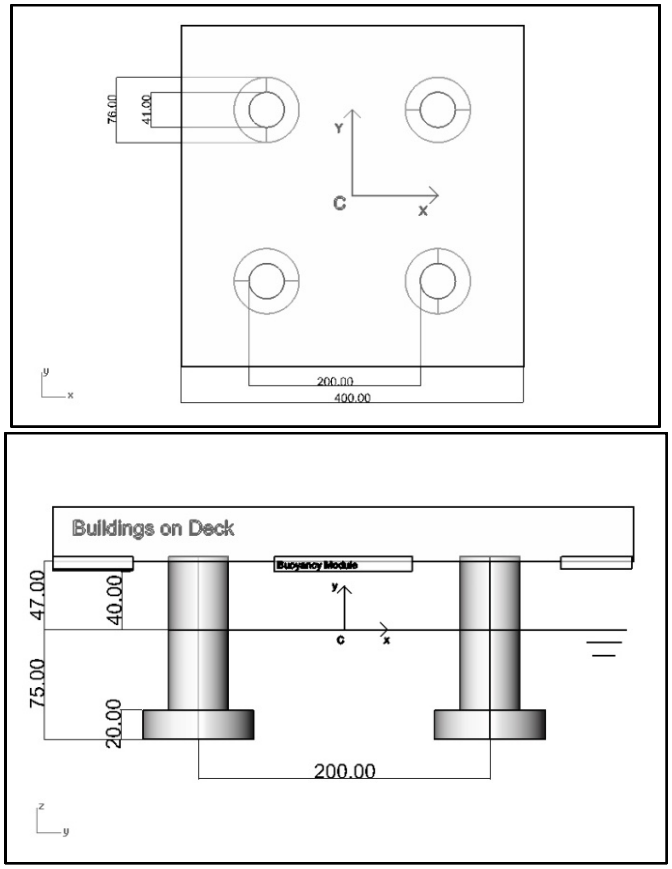

Figure 2: Mean Referential Cxyz on ClubStead platform (left: top view; right: side view)

The Hydrodynamic analysis aims at studying the 6 degree of freedom rigid motions of the platform. The 3 translations (surge, sway and heave) and the three rotations (roll, pitch and yaw) are defined in the following figure:

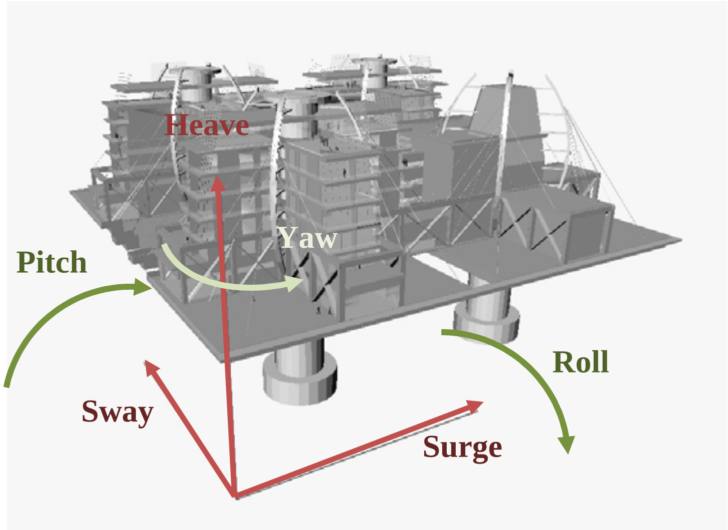

Figure 3: 6 Degree of Freedom Motions

4. Methodology

4.1. Design Requirements

The hydrodynamic analysis predicts the behavior of the ClubStead at its intended location, under specified environmental loads. Rather than using general conservative codes of stability provided by the American Bureau of Shipping [1], this analysis follows API guidelines [2] for numerical hydrodynamic computations. With this approach, the design is optimized for a specific location.

The platform is expected to be located all year round off the coast of San Diego. To comply with survivability requirements, it must be able to survive a 100 year storm without failure. Typically, the pitch and roll angular motions of the platform should be less than 10 degrees at all times. Moreover, green water should not reach the deck level. That means that the wave crest must remain below the bottom of the deck, including the buoyancy module at all times. To ensure a safe design, a clearance of 5ft should be kept between the deck and the wave crest.
The calculations of motions and relative wave height are performed with hydrodynamic program TimeFloat to ensure survivability of the ClubStead in 1 year, 10 year and 100 year storms off the Southern coast of California.

The primary purpose of the ClubStead is its requirement to host a couple hundreds of non-mariners for weeks. Optimized comfort regarding sea motions is critical for the ClubStead to be an attractive destination. Research has shown that comfort at sea depends on vertical acceleration. International standards [3] are available for comparison. For highest level of comfort the standard deviation of the vertical acceleration should remain below 0.25m/s^2 most of the time. TimeFloat is used to compute the time series of acceleration at specific locations in the buildings for sea-states in the wave-scatter diagram.

4.2. Numerical Model

4.2.1. Frequency Analysis with WAMIT

WAMIT is a frequency domain commercial program. It computes the radiation and diffraction loads on a floater due to water waves. It is based on a panel distribution of the potential on the wetted surface of the floater.

WAMIT is run using a high-order description of the geometry with NURBS. The surfaces are generated for one column with the 3D software Rhino. Figure 4 represents the low order mesh equivalent to the B-spline discretization generated by WAMIT.

A convergence analysis is carried out on the panel size used for high order discretizations. With a panel size of 10ft, the results are converged. Convergence plots with panel sizes of 5 and 10ft can be found in the appendix 1 and 2.

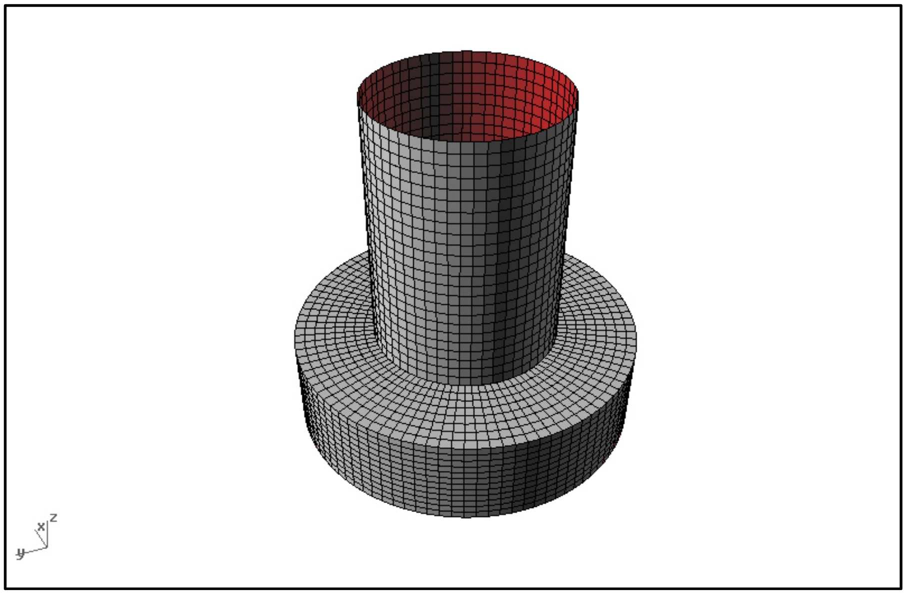

Figure 4: Mesh of a submerged column equivalent to WAMIT NURBS discretization

4.2.2. Time-Domain Analysis with TimeFloat

TimeFloat was developed by MI&T to compute the 6-degree-of-freedom motions of a floater subject to environmental loads, non linear viscous loads due to shedding, mooring forces and any other mechanical forces. The motions of the floater and the tension of the potential tethers are fully coupled.

TimeFloat is a FORTRAN program which advances the solution of the equation of motion in time. Information is provided to the software through an input file in text format, with all vessel, mooring, and numerical parameters. Additional inputs consist of the WAMIT output files and the wind and current coefficients files providing coefficients for headings every 5 degrees between 0 and 360 degrees. The solution is advanced in time using a Runge-Kutta algorithm for the 6 DOF rigid body motions. At each of the 4 fractional steps used in this process, external forces are updated.

TimeFloat uses WAMIT as a hydrodynamic kernel. The frequency-domain analysis provides the hydrodynamic coefficients (added mass, wave damping and hydrostatic stiffness) for the resolution of the 6 degree-of-motion equations. It also computes the diffraction forces due to wave interactions and the 2nd order drift forces based on Newman's linear approximation.

In the frequency-domain, neglecting non-linear forces, Newton's equations of motions are as follows:
$-(M+A)\omega^2 X + B\omega i X + C\,X = F(\omega)$ where X is the 6 degree of freedom (DOF) motion vector, M is the 6x6 mass matrix of the floater, A the added mass, B the linear wave damping matrix and C is the hydrostatic stiffness matrix due to the radiating waves. F is the 6 DOF linear exciting force.

In the time-domain, it can be shown that the equation of motion has the following general form:
$(M+a')\,\ddot{x}(t) + \int_{-\infty}^{t} K(t-\tau)\,\dot{x}(\tau)d\tau + C\,x(t) = F(t)$ where a' is frequency dependent and K is the retardation function.
Assuming a sinusoidal wave exciting force, a solution is $x = X\cos(\omega t)$ and the added mass and damping terms can be derived from:

$$\begin{cases} a' = a(\omega) - \dfrac{1}{\omega}\displaystyle\int_0^{\infty} K(\tau)\sin(\omega\tau)d\tau \\ K(\tau) = \displaystyle\int_0^{\infty} b(\omega)\cos(\omega\tau)d\tau \end{cases}$$

These integrals are calculated numerically. For additional information about the TimeFloat software, on may refer to [4] and [5].

The right hand side of the equation is the sum of all 6-degree of freedom forces applied at the center of the floater on the waterline at each time step:
$F(t) = F_{diff} + F_{wind} + F_{current} + F_{drift} + F_{visc} + F_{spring}$

The wave diffraction forces F_{diff} and the drift forces F_{drift} are obtained by combination of the WAMIT coefficients with a Jonswap wave spectrum, with peakness factor 2.5 at a given significant height Hs and peak period Tp. Such a wave spectrum is typical of ocean waves. A random time series of the wave elevation is generated numerically.

The DP system is modeled with a linear force using soft horizontal springs which are set up at the potential location of the thrusters, 10ft under the waterline to control the motions in surge, sway and yaw. The location of the thrusters has to be confirmed in further design stages.

The wind forces F_w and moments are computed from wind coefficients. The wind coefficients are defined as:

$C_d = \frac{F_w}{\frac{1}{2}\rho A_w V_w^2}$ where ρ is the sea water density, A_w is the projected wind area of the platform and V_w is the wind velocity. The wind velocity is based on the 1-hour wind speed defined by the sea-state combined with a wind spectrum recommended by API RP2SK [2]. The 1 hour wind speed is obtained from the 8 minute averaged wind speed from the NOAA buoys by applying a multiplying factor provided by API.

The surface area of the columns without shielding and the vertical surface area of all levels of the buildings are added to obtain A_w:

Table 5: Wind Properties - Projected Surface Area and Position of Center of Wind Pressure above the waterline

Description	Projected Surface Area (ft2)	Center of Pressure above WL (ft)	Moment (ft3)
Buoyancy module	2320	45	104400
Level 1	10000	62.5	625000
Level 2	6000	82.5	495000
Level 3	5100	97.5	497250
Level 4	5100	112.5	573750
Level 5	3300	127.5	420750
Level 6	3300	142.5	470250
Column 1	1640	20.00	32800
Column 2	1640	20.00	32800
Column 3	1640	20.00	32800
Column 4	1640	20.00	32800
Total	**41680**	**79.60**	

Viscous forces are modeled in TimeFloat with Morison equations. The squared velocity formulation is standard practice in time domain analysis and is known to represent the viscous forces with sufficient accuracy. A drag coefficient (Cd) of 1 is assumed on the cylindrical columns in the horizontal and vertical directions. The current force is also computed using a Morison formulation.

5. Main Characteristics

5.1. Hydrostatic Characteristics

The metacentric height GM is computed to verify the hydrostatic stability of the platform. The metacentric height is the distance from the center of gravity G to the metacenter M:

GM = KB + BM – KG, where KG is the distance between the keel and the center of gravity, KB the distance between the keel and the center of buoyancy and BM the algebraic distance between the center of buoyancy and the metacentre of the platform.

The metacentric height of the ClubStead is 13.8ft, as shown in Table 6. The American Bureau of Shipping (ABS) requires a GM greater than 3ft [1] to classify a marine structure. The hydrostatic characteristics of the ClubStead meet the design criteria.

Table 6: Metacentric Height on ClubStead

	(ft)
KG	94.5
KB	26.7
BM	81.7
GM	**13.8**

5.2. Frequency Analysis

The hydrodynamic behavior of the floater is described in the frequency domain by the Response Amplitude Operator (RAO). The RAOs are defined as the ratio of the RMS[1] of the motion in a degree of freedom to the RMS of wave surface elevation.

WAMIT computes linear RAOs which represent the amplitude of motion of the ClubStead in sinusoidal waves without viscous shedding. They are plotted in Figure 5 to Figure 7 for waves heading 0 degree with periods ranging between 2 and 40 seconds.

The amplification factor of roll and pitch over the range of excitation of ocean waves is lower than 0.2 degree per ft of wave height. The natural period in pitch and roll is out of the range of ocean waves, above 35 seconds. The rolling linear motions on the ClubStead will be small.

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[1] Root Mean Square

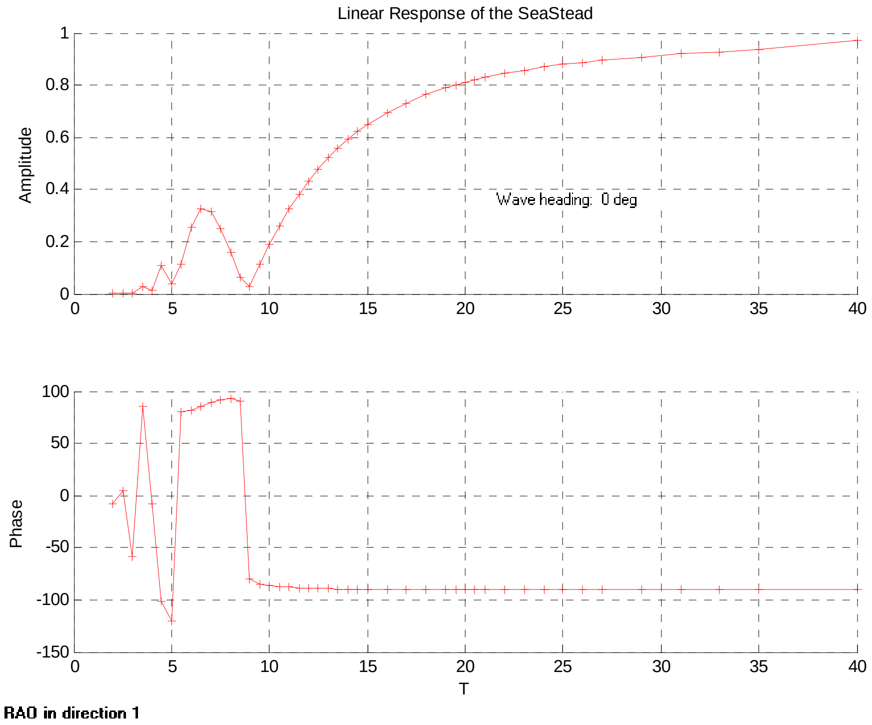

Figure 5: Surge RAO: amplitude (ft/ft) and phase (deg)

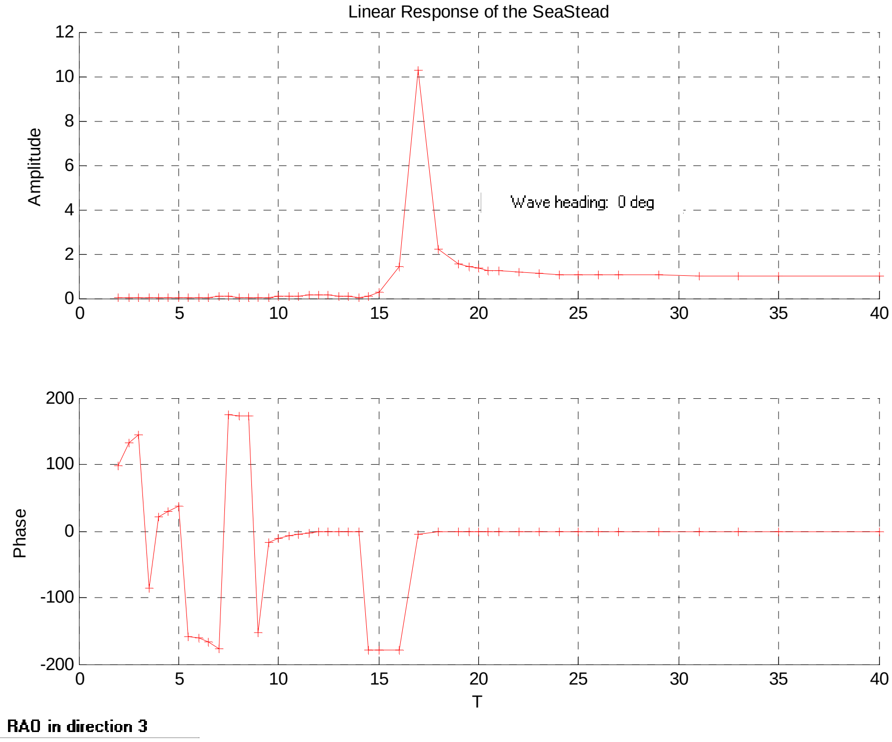

Figure 6: Heave RAO: amplitude (ft/ft) and phase (deg)

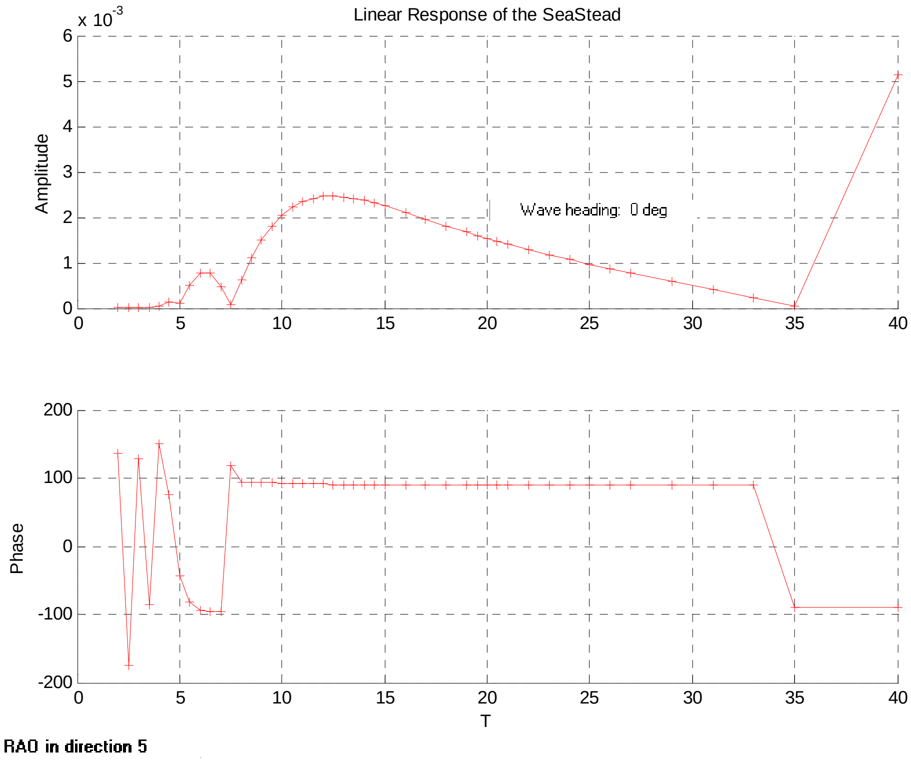

Figure 7: Pitch RAO: amplitude (rad/ft) and phase (deg)

At the heave period of resonance, at a period of 17 seconds, the heave motion is amplified 10 times. This is an overpredicted result due to the lack of damping in potential theory. In reality, the effect of viscous damping will limit the resonant behavior. A sensitivity analysis is carried out on the effect of damping on the heave RAO by applying a linear damping to critical damping ratio between 1% and 10%.

The critical damping in heave is defined as:
$B_0 = 2\sqrt{K_{33}(M + A_{33})}$ where K_{33} is the heave hydrostatic stiffness and A_{33} is the heave added mass.

Results at the heave natural period are shown in Table 7. They are compared with the RAO obtained with TimeFloat when the ClubStead is in regular waves. In TimeFloat, due to the nonlinearity of the viscous forces the result is dependent on the wave height. The RAO in heave from TimeFloat is plotted for wave heights of 10, 20 and 30ft to represent the range of waves encountered by the ClubStead. The corresponding linear damping in WAMIT is about 3% of critical damping. Model tests are usually required to quantify damping that needs to be applied to the WAMIT formulation.
At large periods, the heave amplification factor converges to 1, which means that the platform will move up and down with such waves.

Table 7: Effect of Damping on the Heave RAO

Damping Ratio	RA0 at 17sec	Damping (slug/sec)
0%	9.8	0
1%	7.0	1.80E+04
3%	3.3	5.40E+04
5%	2.1	9.01E+04
10%	1.2	1.80E+05

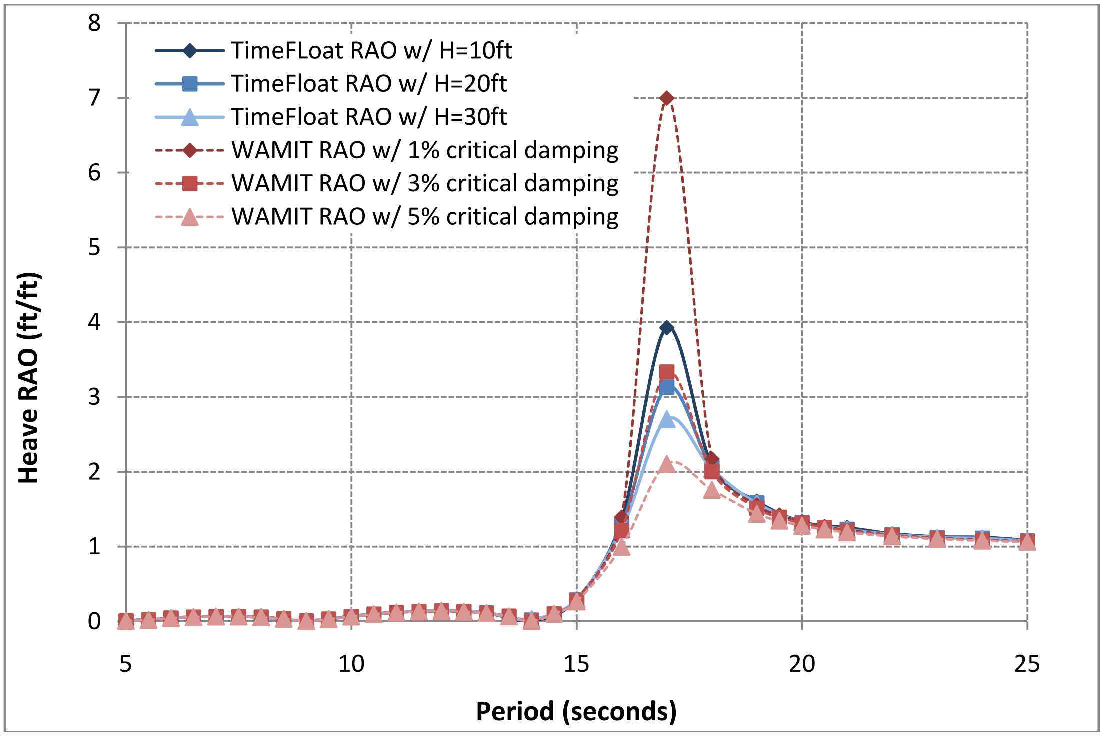

Figure 8: Effect of Damping on the Heave RAO

6. Survivability Analysis in Extreme Sea-States

To verify the behavior of the ClubStead in extreme weather conditions, 3-hour simulations of the 1 year, 10 year and 100 year storms off the coast of San Diego, California are run with TimeFloat. The characteristics of the sea-states are recalled in Table 8.

Table 8: Extreme Sea-States off San Diego, CA

Return Period		**1 year**	**10 year**	**100 year**
Hs	*m*	7.0	7.7	8.3
Tp	*s*	14.3	14.3	14.3
8 minute Gust Speed	*m/s*	16.0	17.5	18.9
Current Speed	*m/s*	0.48	0.53	0.57

Forces and motions are calculated for 0 degree and 45 degree heading waves and wind. Headings between 45 and 360 degrees need not be considered since the platform is symmetrical.

6.1. Results

Times series of the 6 degree of freedom motions of the platform are generated for each sea-state during a 3-hour simulation. Results are plotted for the 100 year storm, with a significant wave height of 27.23ft, in Figure 9 and Figure 10. The first few minutes of the simulation are not relevant since they reflect the numerical transients.

Overall, the pitch and roll angles remain below 5 degrees, which indicates that the platform is stable.

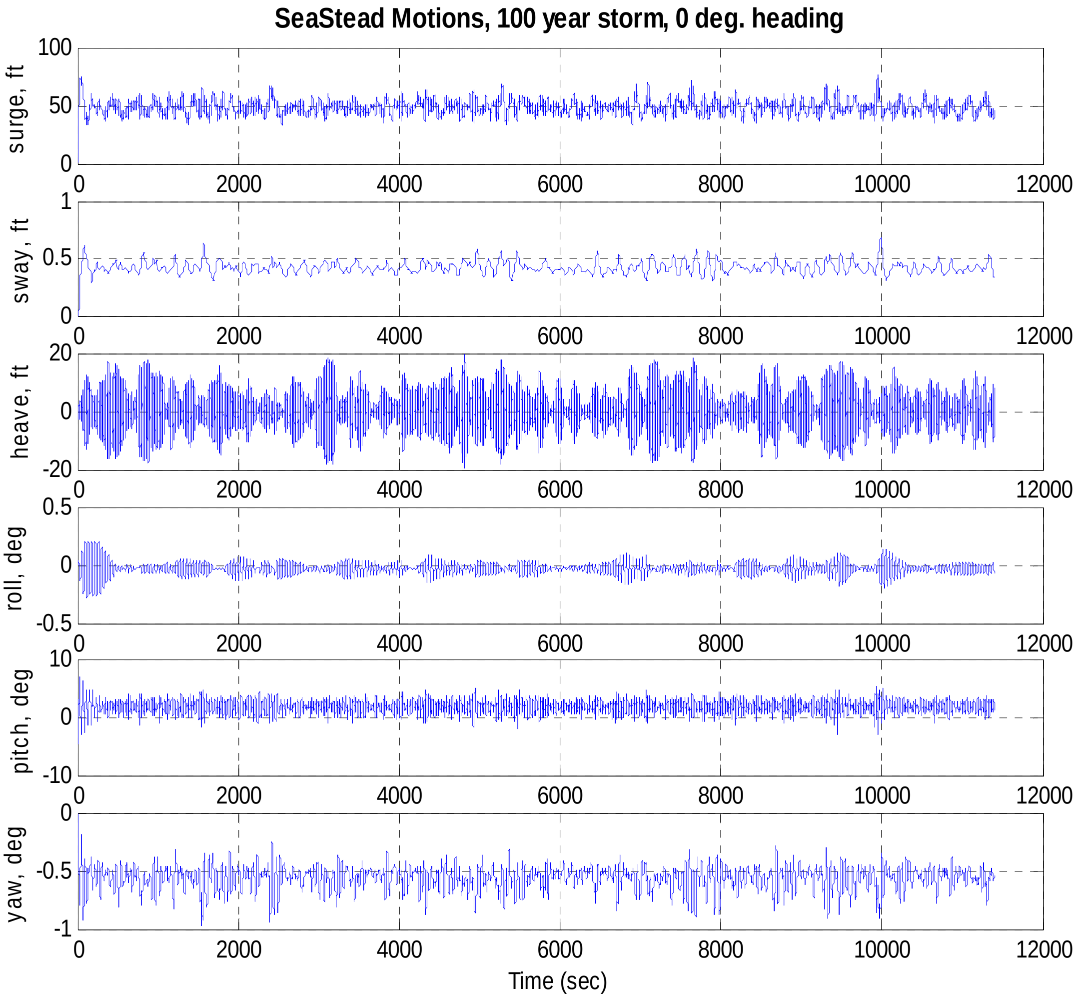

Figure 9: Motions of ClubStead in a 3-hour simulation of 100 year Storm, with 0 deg. heading

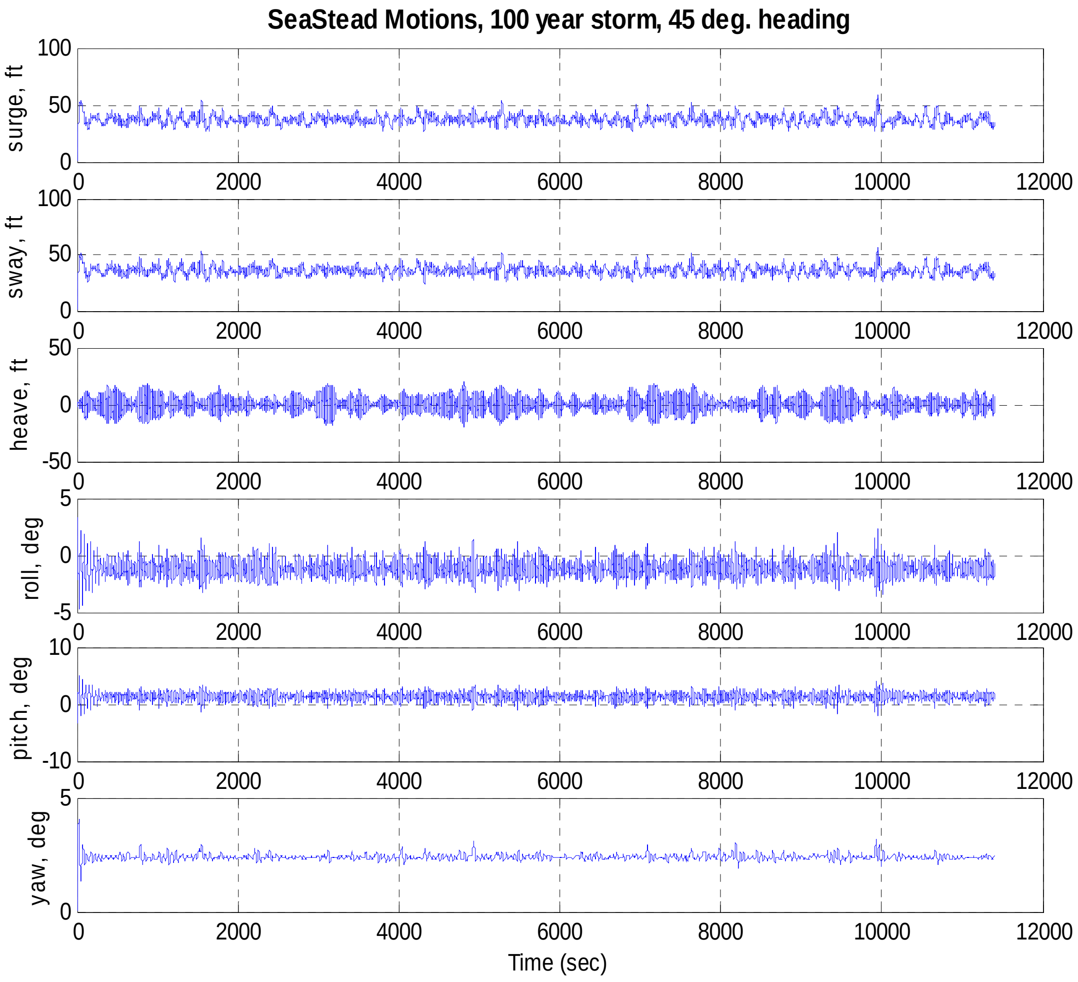

Figure 10: Motions of ClubStead in a 3-hour simulation of 100 year Storm, with 45 deg. heading

Wave gages are numerically placed at the lowest level of the deck throughout the platform. Their coordinates in the mean frame of reference are listed in Table 9. Wave gages 1 to 4 are located at the 4 corners of the platforms, at the bottom of the suspended surface areas. Wave gages 5 and 6 are located at the lower forward extremities of the buoyancy module, 40ft above the mean waterline.

Table 9: Coordinates of Wave Gages in ClubStead Referential

Name	X	Y	Z
	ft	ft	ft
wavgage1	-200	-200	47
wavgage2	-200	200	47
wavgage3	200	-200	47
wavgage4	200	200	47
wavgage5	200	125	40
wavgage6	200	-125	40

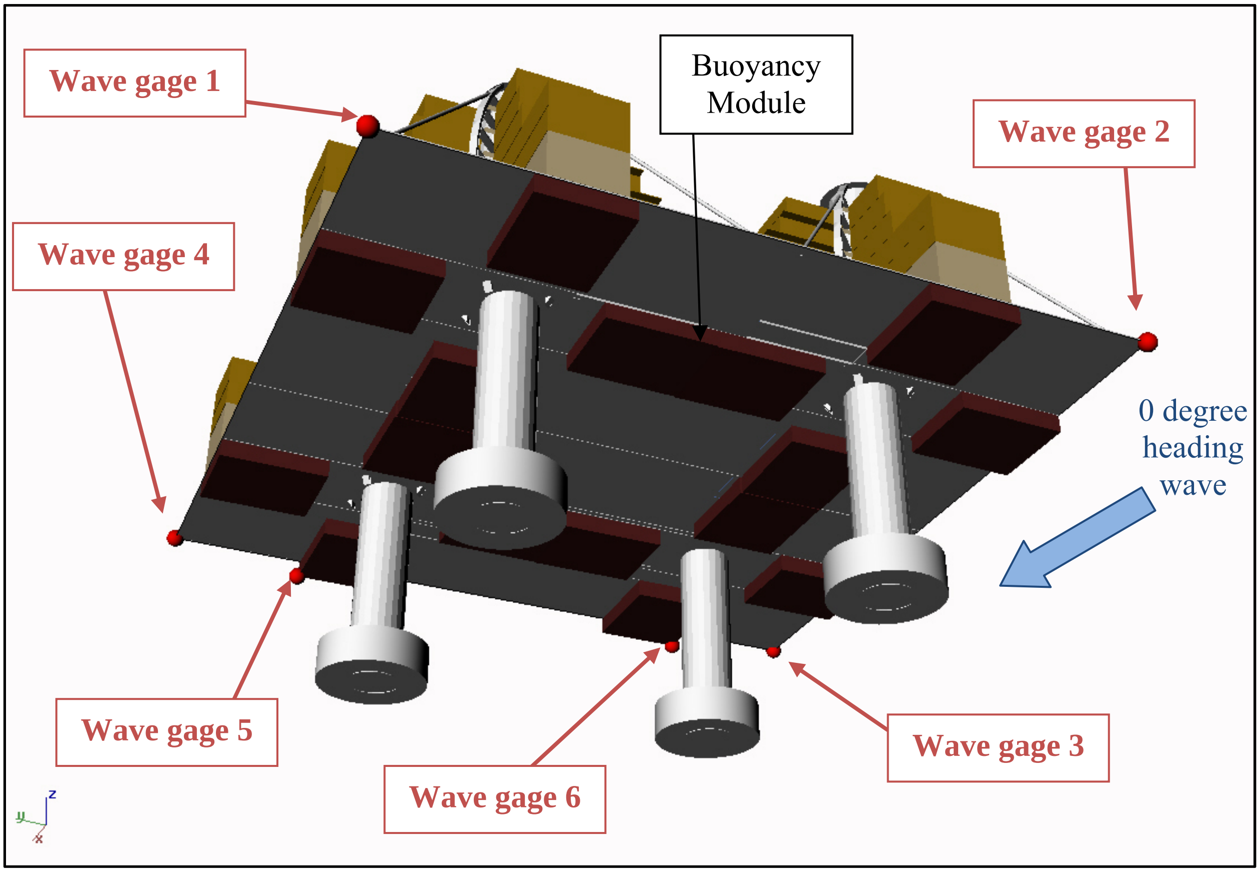

Figure 11: Location of Wave Gages under the deck

Wave gages in TimeFloat compute the difference between the vertical coordinate of a given point above the waterline and the local height of the wave crest. They provide a measurement of the clearance between the wave crest and the deck at all times. If the wave gage returns a negative number, it means green water hits the deck and damage may be caused from wave forces.

Time series of the distance between deck and wave crest are shown in Figure 12 and Figure 13 in the 100 year storms. The deck and buoyancy modules are above the wave crest at all times. A 5ft clearance is provided between the highest wave crest and the tip of the buoyancy module. The clearance is larger than 9ft for the extremities of the suspended surface areas, located 47ft above the mean waterline.

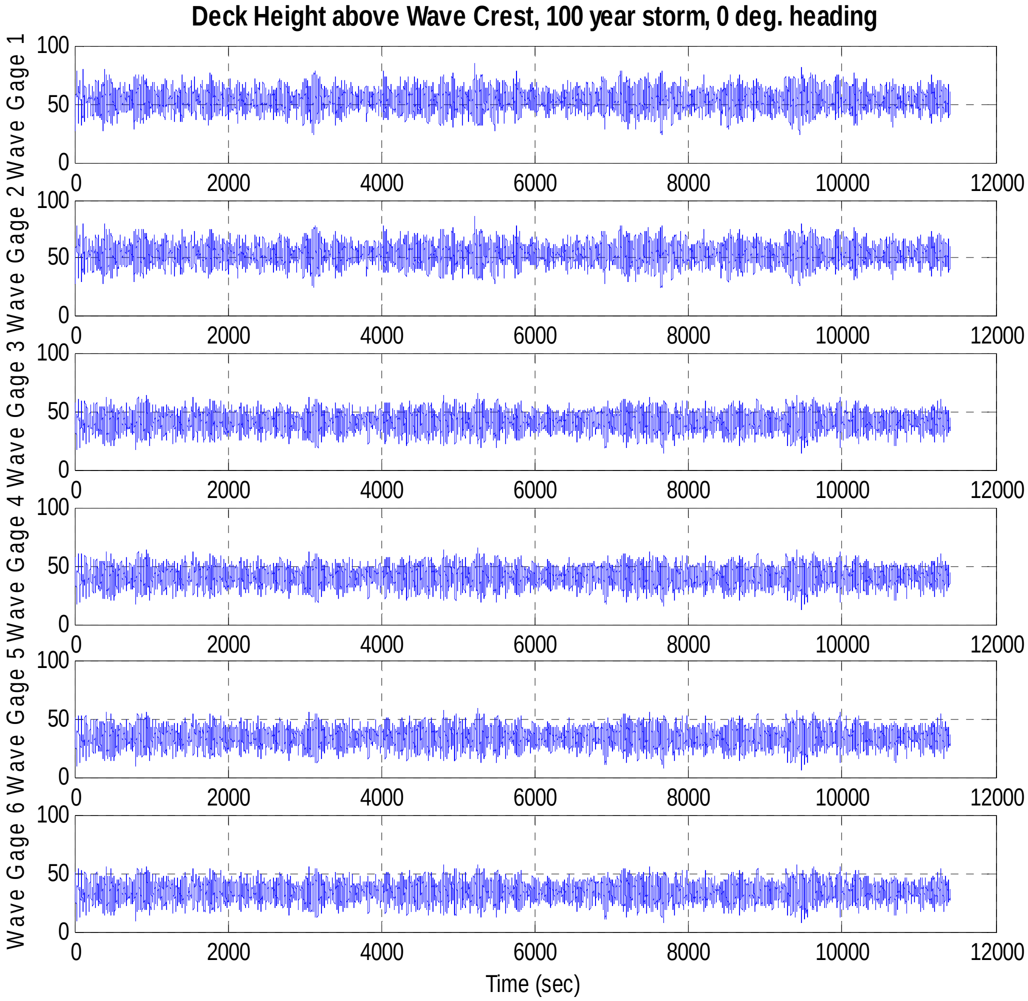

Figure 12: Relative Height of Deck above Wave Crest (ft) at deck extremities, 100 year storm, 0 deg. heading

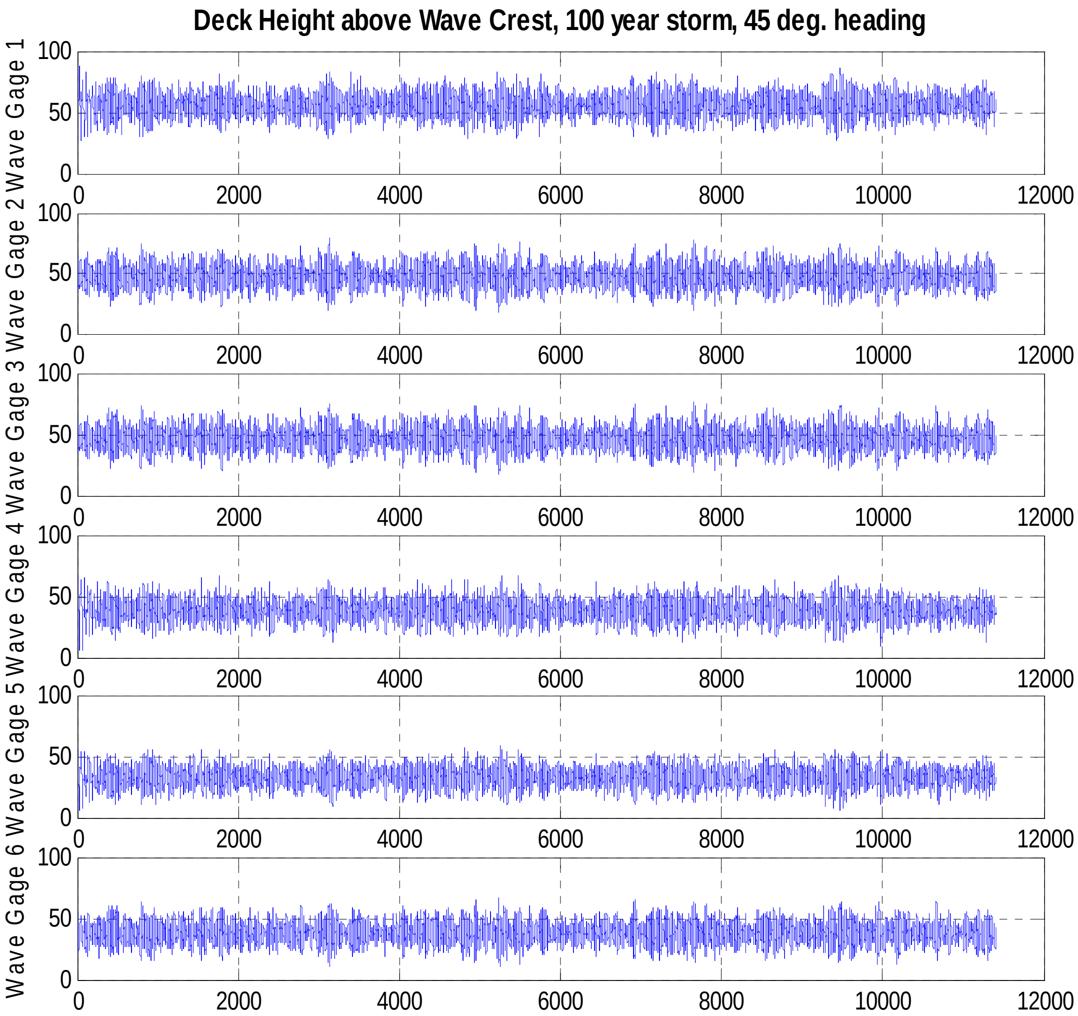

Figure 13: Relative Height of Deck above Wave Crest (ft) at extremities of deck, 100 year storm, 45deg heading

Statistics of motions and of the wave gage computations are provided for each 3-hour storm. The survivability criteria are met in all cases.

Table 10: Statistics of Motions in Extreme Sea-States (All units are in ft)

1 year - 0 deg		Mean	RMS	Max	Min
Wave	height	0.08	5.73	23.26	-24.53
Motions	surge	30.61	4.40	51.91	18.47
	sway	0.22	0.02	0.31	0.16
	heave	-0.01	5.61	16.81	-17.02
	roll	-0.02	0.03	0.07	-0.10
	pitch	1.26	0.79	4.22	-2.57
	yaw	-0.40	0.05	-0.22	-0.67
Wave Gages	1	51.42	7.26	78.08	25.29
	2	51.31	7.24	78.15	25.41
	3	42.65	6.51	62.75	18.43
	4	42.54	6.52	63.07	18.48
	5	35.56	6.51	56.01	11.46
	6	35.63	6.51	55.80	11.43

1 year - 45 deg		Mean	RMS	Max	Min
Wave	height	0.11	5.73	23.28	-24.53
Motions	surge	24.51	3.05	40.79	15.53
	sway	23.80	3.06	39.54	14.65
	heave	0.00	5.60	16.65	-17.20
	roll	-0.86	0.56	1.93	-2.87
	pitch	0.92	0.55	2.97	-1.85
	yaw	1.76	0.09	2.31	1.38
Wave Gages	1	53.20	7.39	78.79	29.75
	2	47.12	7.71	74.87	20.07
	3	46.71	7.65	74.13	20.80
	4	40.84	6.96	64.75	16.89
	5	34.94	6.53	57.32	11.53
	6	38.60	7.36	63.26	15.65

10 year - 0 deg		Mean	RMS	Max	Min
Wave	height	0.10	6.30	25.62	-26.99
Motions	surge	39.34	5.10	64.14	25.09
	sway	0.31	0.03	0.48	0.21
	heave	-0.01	6.05	18.33	-18.55
	roll	-0.02	0.03	0.10	-0.14
	pitch	1.50	0.89	4.85	-2.85
	yaw	-0.48	0.07	-0.25	-0.84
Wave Gages	1	52.29	7.91	81.73	23.86
	2	52.12	7.89	82.08	23.98
	3	41.82	7.07	63.97	16.20
	4	41.67	7.08	64.29	15.80
	5	34.70	7.08	57.19	8.92
	6	34.80	7.07	57.01	9.19

10 year - 45 deg		Mean	RMS	Max	Min
Wave	height	0.13	6.30	25.53	-26.88
Motions	surge	30.75	3.53	49.61	20.55
	sway	29.72	3.52	47.81	19.43
	heave	0.00	6.03	18.14	-18.76
	roll	-1.02	0.62	2.13	-3.29
	pitch	1.10	0.61	3.44	-2.03
	yaw	2.08	0.11	2.75	1.64
Wave Gages	1	54.41	8.07	83.04	28.49
	2	47.19	8.39	77.27	17.95
	3	46.60	8.30	75.49	18.85
	4	39.65	7.60	66.21	12.81
	5	33.95	7.10	58.10	8.99
	6	38.30	7.98	64.94	13.64

100 year - 0 deg		Mean	RMS	Max	Min
Wave	height	0.11	6.79	27.34	-28.96
Motions	surge	48.36	5.73	76.18	32.36
	sway	0.42	0.05	0.69	0.30
	heave	-0.01	6.42	19.56	-19.86
	roll	-0.03	0.05	0.13	-0.20
	pitch	1.76	0.97	5.45	-3.10
	yaw	-0.56	0.10	-0.26	-0.98
Wave Gages	1	53.19	8.47	85.31	22.79
	2	52.97	8.44	85.56	23.07
	3	40.97	7.55	64.86	13.70
	4	40.75	7.57	65.30	12.65
	5	33.79	7.56	58.17	5.83
	6	33.93	7.55	57.90	6.49

100 year - 45 deg		Mean	RMS	Max	Min
Wave	height	0.16	6.79	27.21	-28.71
Motions	surge	37.24	3.98	58.56	25.87
	sway	35.83	3.94	56.13	24.47
	heave	0.00	6.40	19.38	-20.08
	roll	-1.18	0.68	2.30	-3.70
	pitch	1.30	0.67	3.90	-2.17
	yaw	2.40	0.12	3.20	1.92
Wave Gages	1	55.66	8.66	86.55	27.25
	2	47.28	8.96	79.40	16.54
	3	46.48	8.85	76.14	17.05
	4	38.40	8.15	66.84	9.35
	5	32.92	7.59	58.25	6.08
	6	37.96	8.50	66.17	10.87

6.2. Sensitivities and Discussion

A sensitivity analysis is carried out to verify the robustness of the results.
1-hour simulations of the 100 year storm are run to determine the sensitivity of the results to variables such as drag coefficients on the footing, wind coefficients and wave period. They are compared against the 1-hour simulations of the base case.

When the drag coefficient on the footing of the columns increases from 0.8 to 1.2, the heave motion is reduced and inherently increases the clearance between the wave crest and the deck, as shown in Figure 14. Although the modification is not large, it highlights the need for model tests to verify and confirm the numerical assumptions.

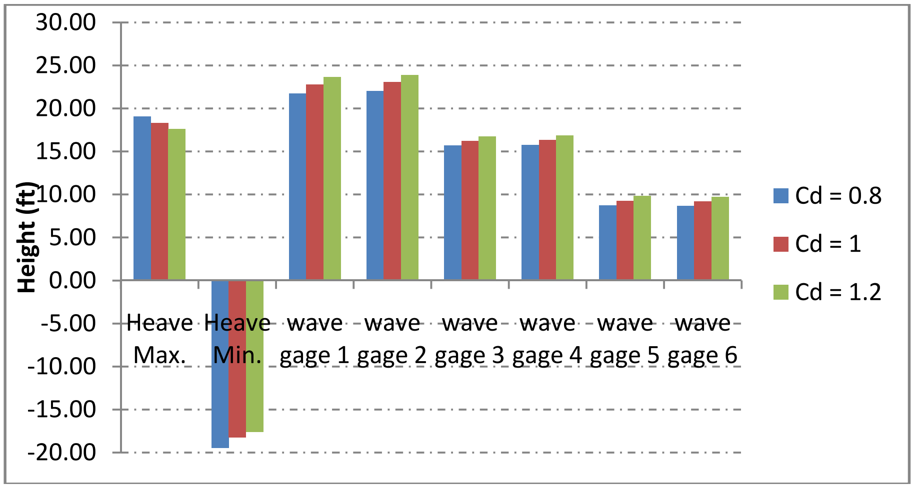

Figure 14: Sensitivity of heave and minimum relative deck height; 1-hour simulation of 100 year storm at 0 deg. heading

The drag coefficient for wind calculation is increased by 10% to determine the sensitivity of the results to the wind coefficients. Results are plotted in **Error! Reference source not found.**.

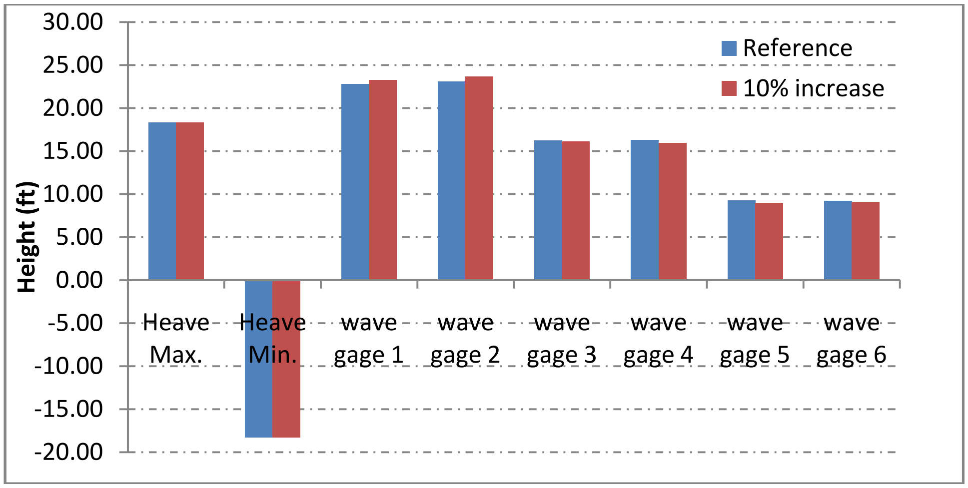

Figure 15: Variation of Heave and Minimum Relative Deck Height with wind coefficients; based on 1 hour simulation of 100 year storm at 0 deg

Additional sensitivities are performed on the effect of the sea-state.

In Figure 16, the results of a 1-hour simulation with significant wave height Hs=27.23ft, are compared for peak period Tp =14.3 and 16.7sec. At 16.7sec, the wave period is equal to the natural period of the ClubStead in heave.

The resonance increases significantly the amplitude of heave motion and decreases the clearance between the deck and the wave crest. If the ClubStead was to withstand very long period swells, the buoyancy module may have to be brought up to the upper deck level and included in the architecture of the lower levels of the buildings. At this stage, this is a minor modification of the topsides which would ensure a more conservative design. Alternative modifications may be considered: the heave period as well as the viscous shedding on the footing could be increased by adding flat horizontal extension along the circumference of the cylinder at the keel. Such adjustments will not affect the overall design.

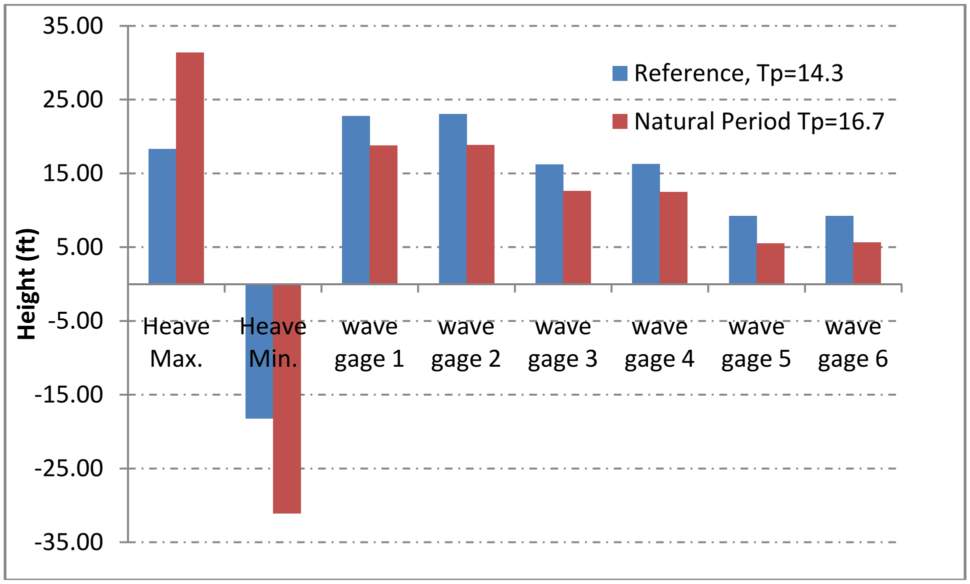

Figure 16: Variation of Heave and Minimum Relative Deck Height with Tp; based on 1 hour simulation of 100 year storm at 0 deg

Finally, although numerical predictions of wave-induced motions are extremely reliable, further verifications may be required with model tests. It is standard practice in offshore platform design to perform such experimental analysis to ascertain numerical viscous parameters and obtain accurate measurements of the run up on the platform, and to validate the overall behavior of the numerical tools.

7. Passenger Comfort in Operational Sea-States

7.1. The ISO 2631 Standard

Standards are available to assess the level of comfort aboard the ClubStead. Research [5] has shown that passenger comfort depends primarily on the acceleration associated with vertical vibrations. Figure 17 shows the limits of standard deviations of acceleration which will result in a majority of the passengers being sea-sick according to the International Standard ISO 2631 [6]. Such limits vary with the time of exposure.

No data was found for periods above 10 seconds. The horizontal asymptotes at low frequencies are extended for these periods. Thus the 8-hour threshold for Tp larger than 10 seconds is assumed to be 0.25m/s^2 as well.

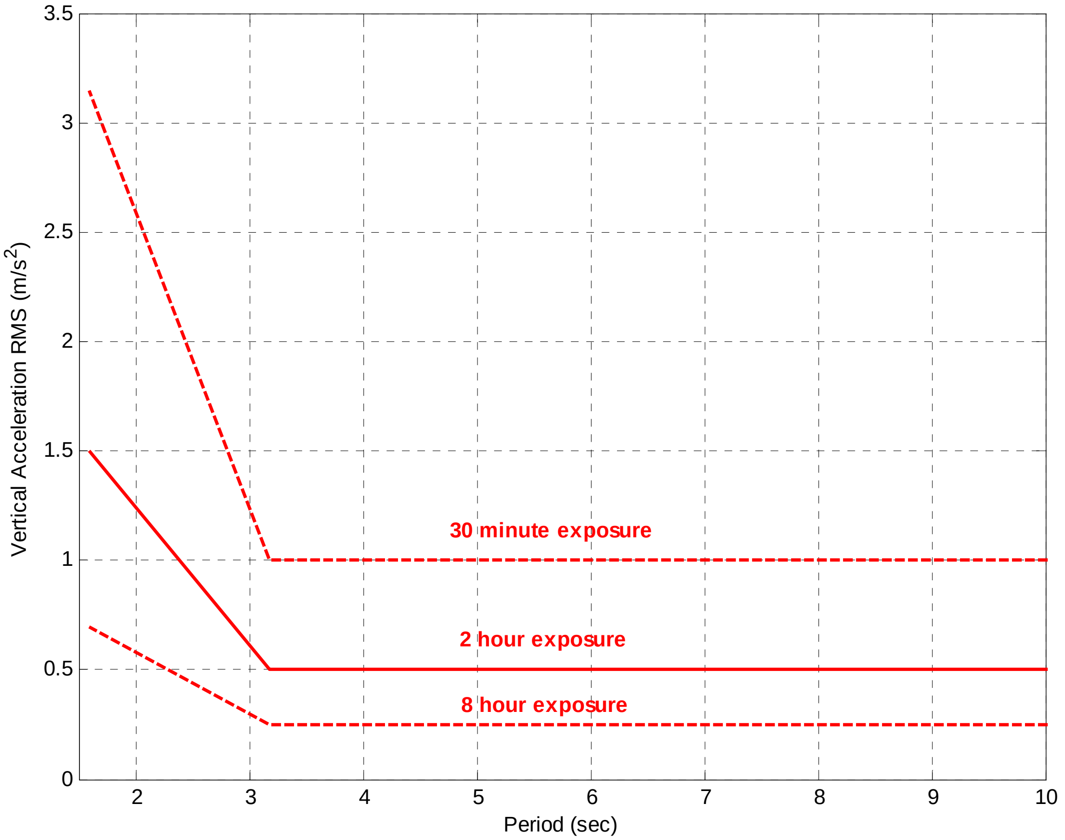

Figure 17: International Standard ISO2631 /3 for severe motion discomfort

7.2. The ClubStead behavior in operational conditions

The 8-hour exposure curve is used in this section to assess the level of comfort aboard the ClubStead. The RMS of vertical acceleration is computed over 1-hour TimeFloat simulations for all sea-states in the wave scatter diagram off San Diego, CA [7]. The waves at 0 degree heading are combined with the most probable 1-hour mean wind velocity at the given significant wave height.

The vertical acceleration at a given point of the deck and buildings is a combination of heave acceleration and pitch and roll rotational acceleration. The impact of location on the platform is investigated by comparing the level of motion sickness at different points of the platform: at the center of the deck (location #1), at the corner extremities of the platform (location #2 and 3) and on top of a tower (location #4 and 5).

Table 11: Coordinates of Location for Estimate of Motion Sickness

	x (ft)	y (ft)	z (ft)
1	0	0	50
2	-200	-200	50
3	200	200	50
4	100	100	150
5	-100	-100	150

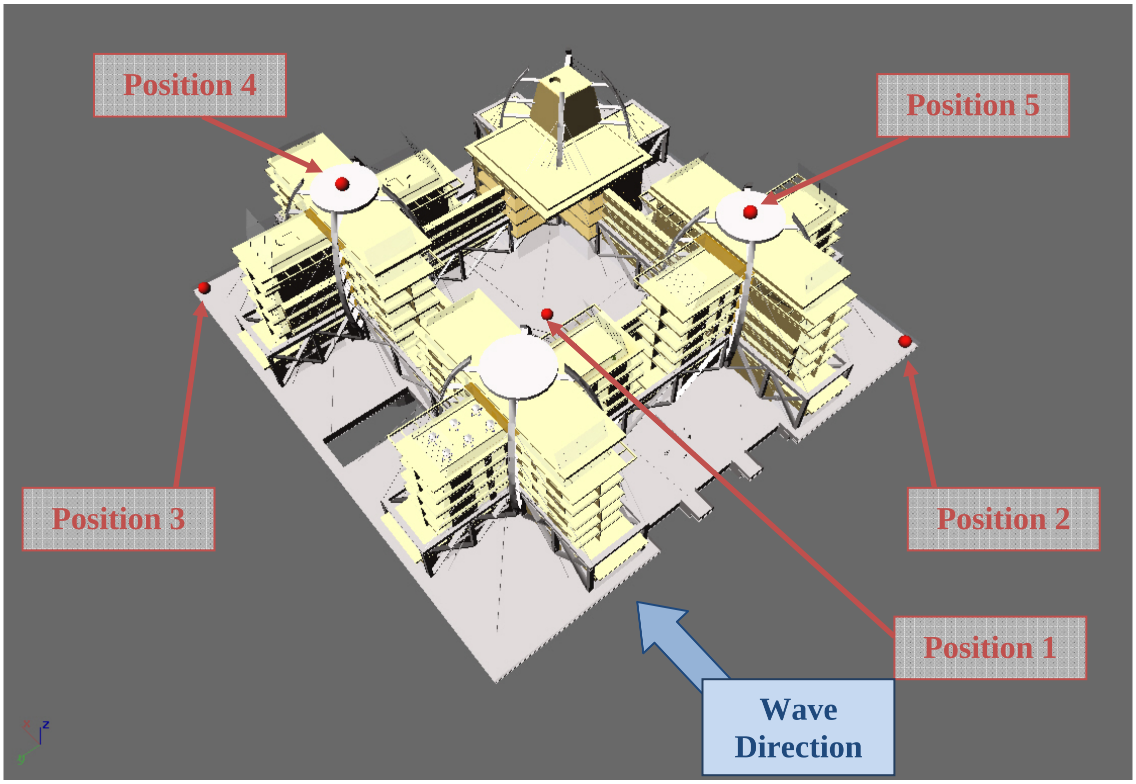

Figure 18: Locations at which Motion Sickness is estimated

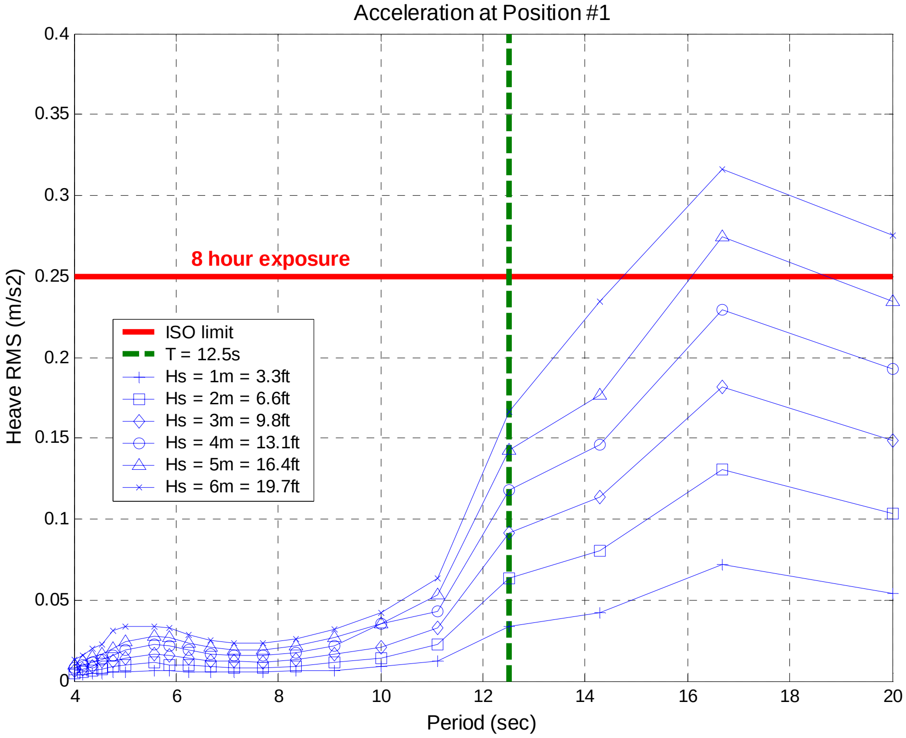

Figure 19: RMS of vertical acceleration - center of deck

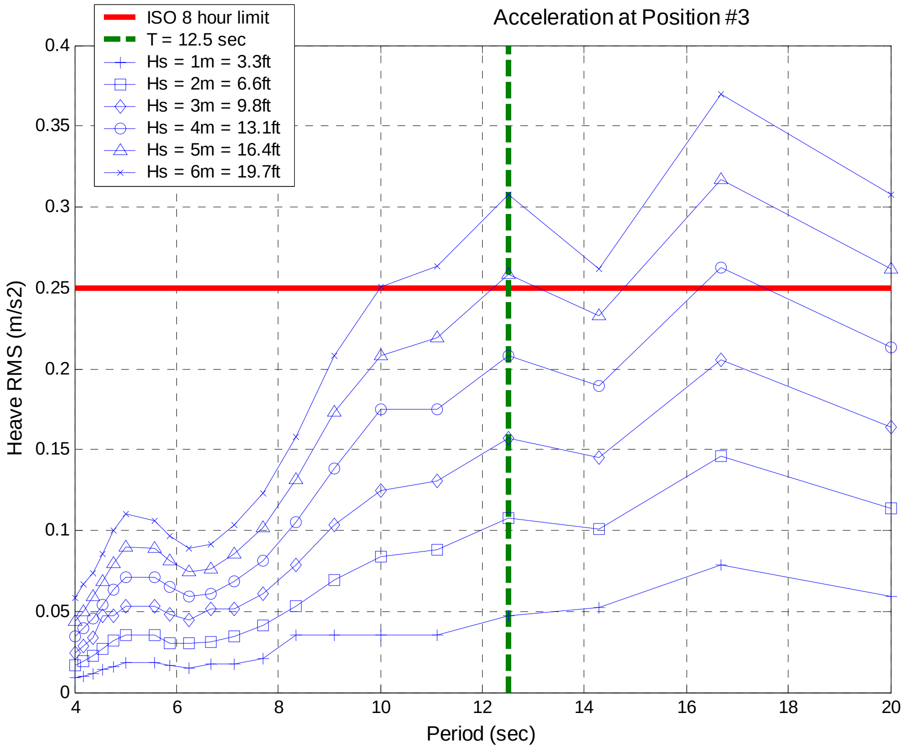

Figure 20: RMS of vertical acceleration - extremity of deck

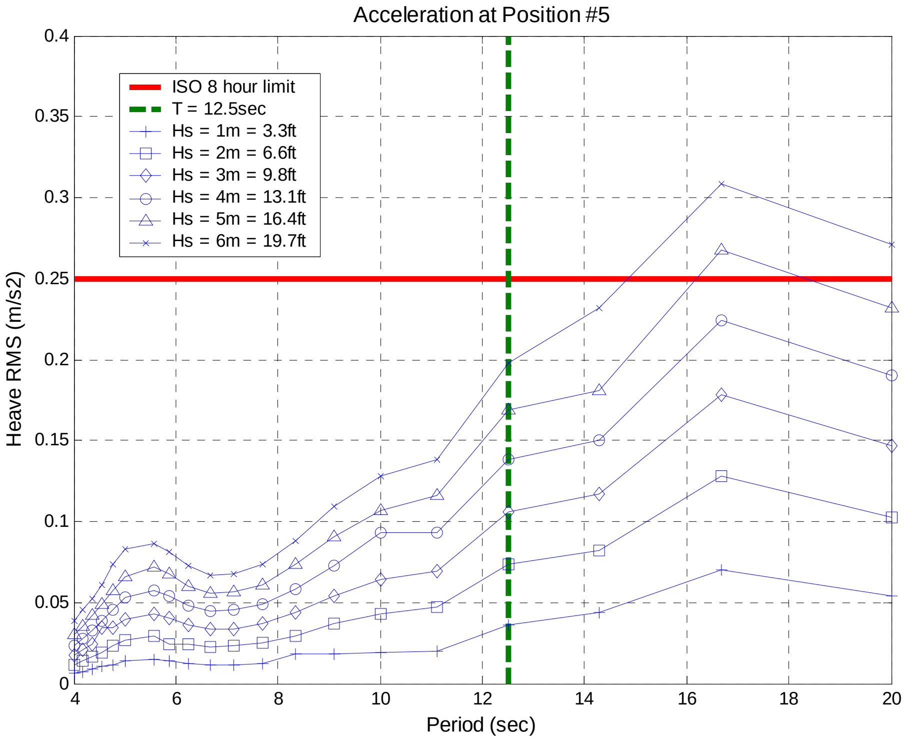

Figure 21: RMS of vertical acceleration - top of tower

Figure 19 to Figure 21 show the variations of vertical acceleration with wave period and significant wave height. Discomfort increases with significant wave height. The wave period has the most significant effect on comfort. As the wave period gets closer to the heave resonance, at 17 sec, the discomfort level increases. Notably, the discomfort level increases also on the extremities of the platform for Tp=12.5sec (see vertical line in Figure 19). This is consistent with the increase in pitch and roll observed at these periods in the RAO of Figure 7.

The location on the platform is also critical to determine the prevalence of motion sickness: a passenger located at point 1 will be much less likely to be sick than a passenger located at point 3. This illustrates the importance of pitch and roll-related vertical acceleration at the tip of the platform.

To estimate the probability of occurrence of each level of motion sickness, the sea-states are associated with their probability of occurrence from the wave scatter diagram described in the Metocean report [7]. The probability of occurrence of each level of motion sickness is calculated by summing the probabilities of the sea-states.

A comparison between the 45 degree and the 0 degree heading cases do not show any significant differences. The above results may be interpreted as heading independent.

Table 12: Probability of occurrence of vertical acceleration (%)

	Probability of Occurrence (%) of Vertical Acceleration > than	
Position	0.1 m/s2	0.2m/s2
1	43	5
2	65	6
3	72	15
4	48	6
5	48	5

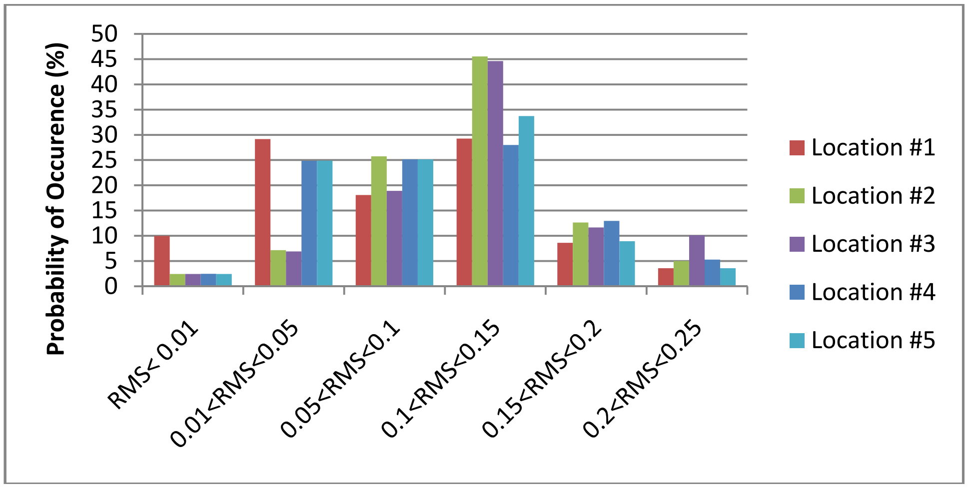

Figure 22: Probability of Occurrence of Vertical Acceleration RMS Values

7.3. For comparison: behavior of a ship shape vessel

To assess the performance of the ClubStead in operational sea-state, it is compared with the behavior of a ship shape boat whose dimensions are given in Table 13.

Table 13: Dimensions of ship shape vessel

Length OA	ft	246.1
Length between perpendicular	ft	233.9
Breadth	ft	56.8
Depth	ft	23.0
Draft	ft	14.4
Volume	ft^3	152,808
weight	st	4,879

The RMS of vertical acceleration is computed on the ship-shape boat at mid-ship and at the bow in 1-hour simulations of head seas, with 2m significant wave height.

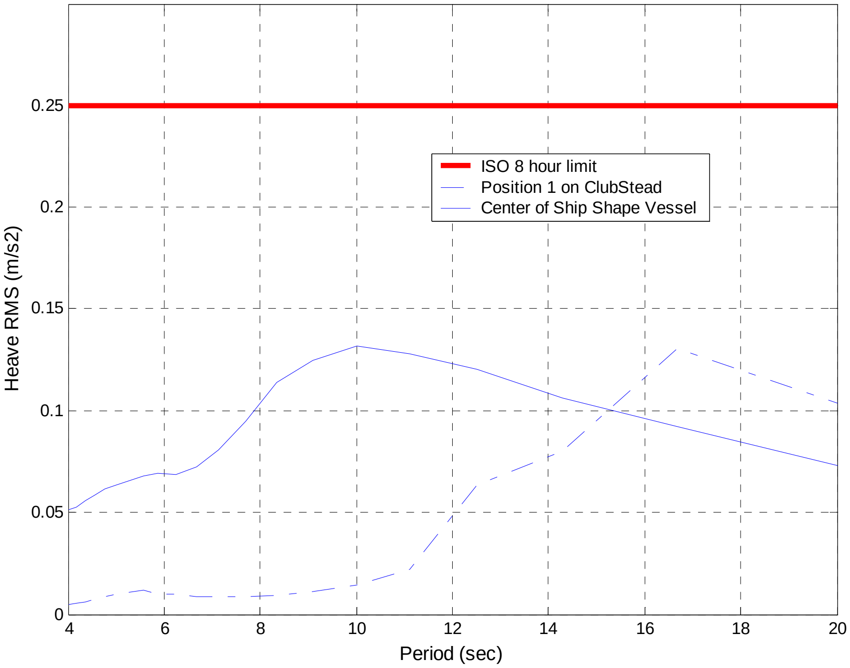

Figure 23: Comparison of Comfort Level at center of Clubstead and center of ship-shape vessel

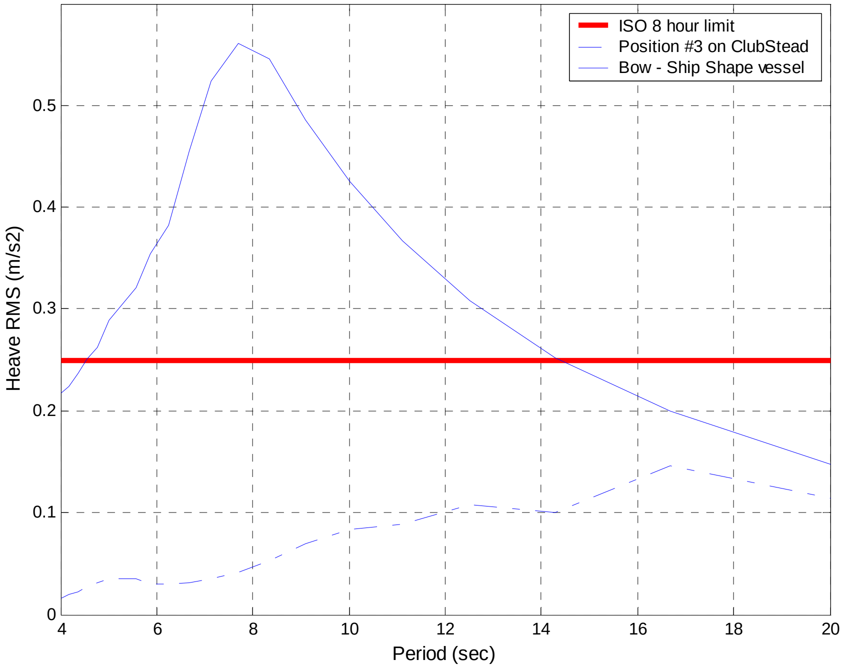

Figure 24: Comparison of comfort level at top of tower on ClubStead and bow on ship-shape vessel

The level of comfort is comparable at mid-ship on the ship shape vessel and on the ClubStead, with all RMS of vertical acceleration below 0.15m/s^2. However the RMS on the ship shape vessel is larger at higher frequencies, corresponding to periods between 7 and 10 seconds. The ClubStead has a much better behavior for periods under 10 seconds, with RMS as low as 0.01m/s^2.

The performance of the ClubStead is even more remarkable when vertical acceleration RMS are compared at the extremities of the vessels. In Figure 24, the RMS of vertical acceleration at the bow of the ship shape vessel is greater than 0.1m/s^2 for all periods with a significant wave height of 6.6ft.

This analysis confirms the good performance of the ClubStead for passenger comfort. Nevertheless, the ship shape vessel mentioned above may not be optimized for long term comfort. Access to motion sickness data for a cruise ship would provide a more accurate assessment of the ClubStead.

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[1] Rules for Building and Classing Mobile Offshore Drilling Units, American Bureau of Shipping, 2001

[2] API RP 2SK, Recommended Practice for Design and Analysis of Stationkeeping Systems for Floating Structures, American Petroleum Institute (API), 2005

[3] C. Cermelli, D. Roddier, A. Aubault, “WindFloat, a Floating Foundation for Offshore Wind Turbines: Hydrodynamic Analysis”, *OMAE 2009*, Honolulu, HI, USA

[4] Cermelli, CA, Roddier DG, and Busso, CC, “MINIFLOAT: A Novel Concept of Minimal Floating Platform for Marginal Fields Development”, *Proc. of 14th Intl. Offshore and Polar Engrg Conf (ISOPE),* Toulon, France, 2004

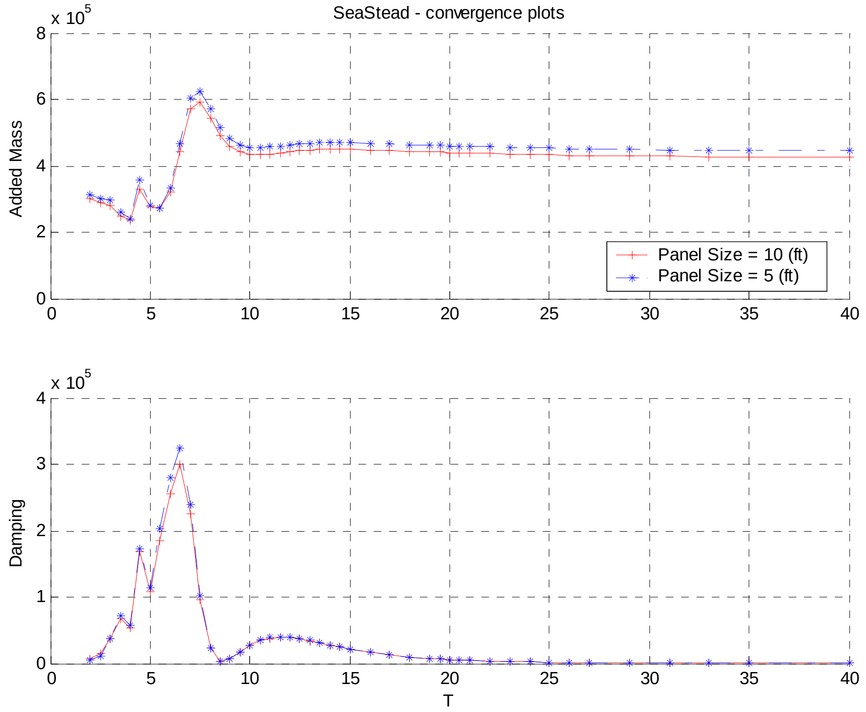
[5] O’Hanlon, J.P. and McCauley, M.E., 1974, “Motion Sickness Incidence as a Function of the Frequency and Acceleration of Vertical Sinusoidal Motion”, Aerospace Medicine, 45(4):366-369.

[6] International Organization for Standardization, Specification 2631-1:1997, *Mechanical vibration and shock – Evaluation of human exposure to whole-body vibration – Part 1: General requirements.*

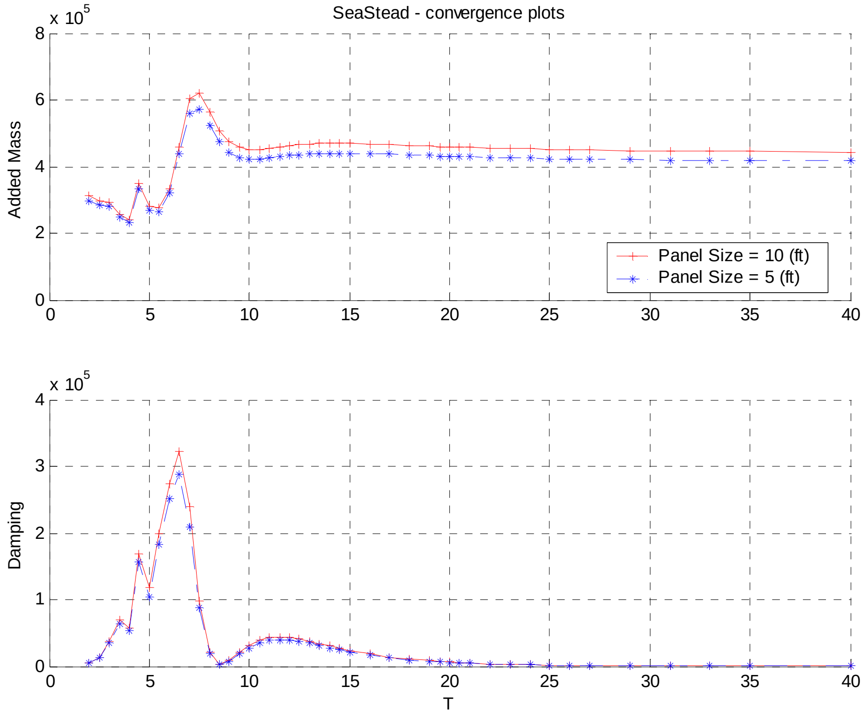
[7] “ClubStead Preliminary Analysis: Metocean Analysis”, MI&T, March 2009

[8] WAMIT user manual

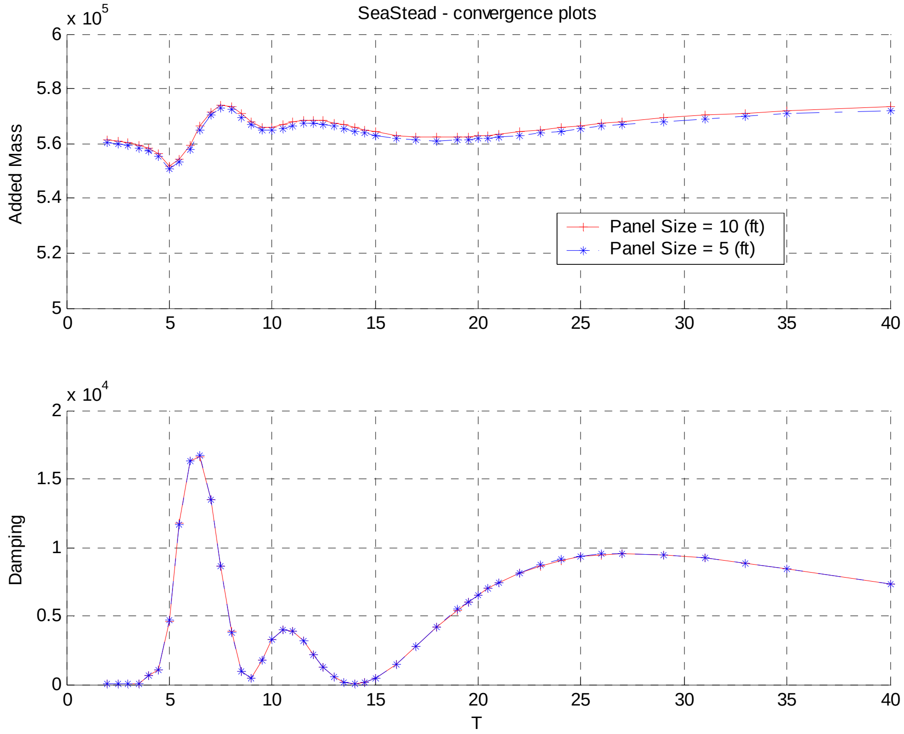
Appendix 1. Hydrodynamic Coefficients from WAMIT



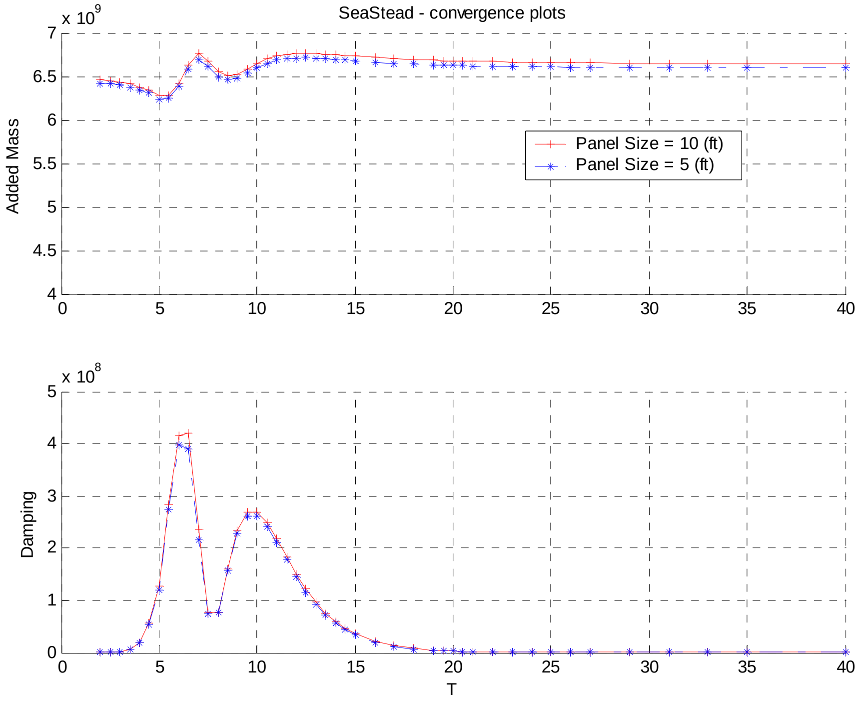
Hydrodynamic coefs in direction 1 1



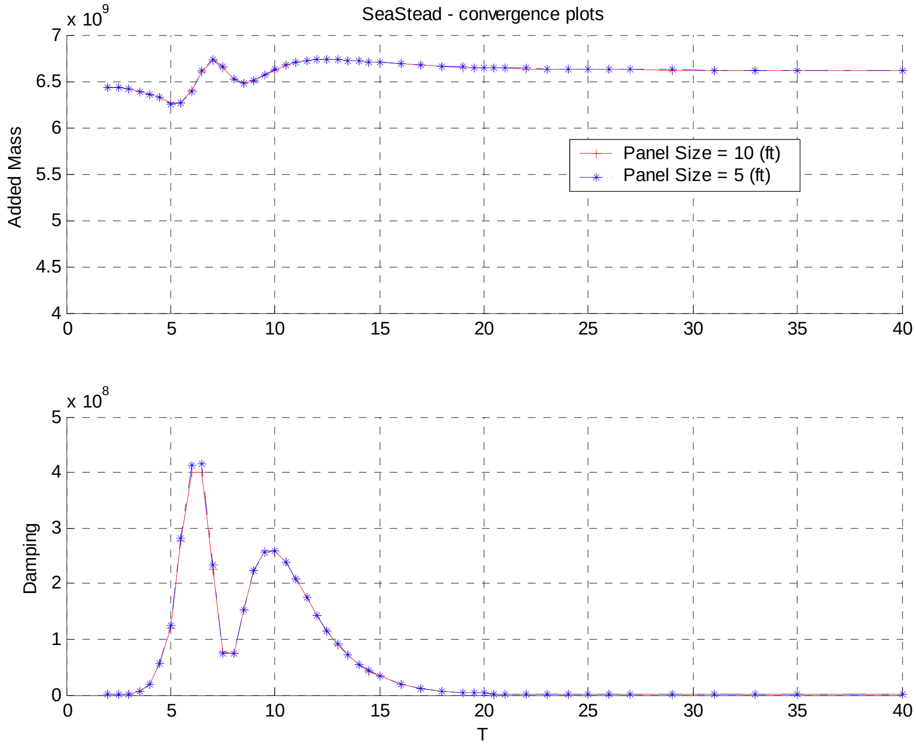
Hydrodynamic coefs in direction 2 2



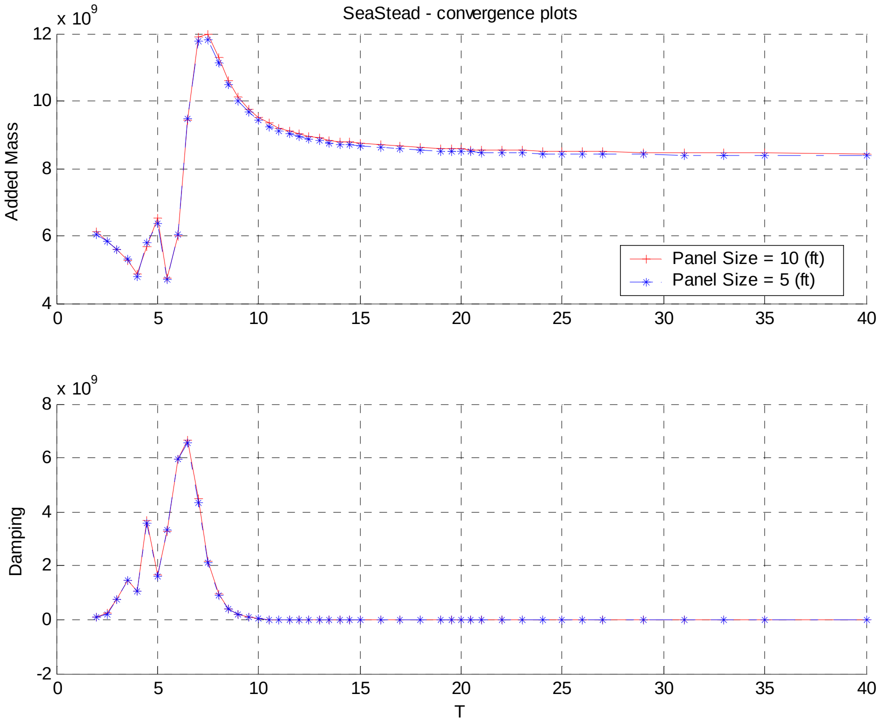
Hydrodynamic coefs in direction 3 3



Hydrodynamic coefs in direction 4 4

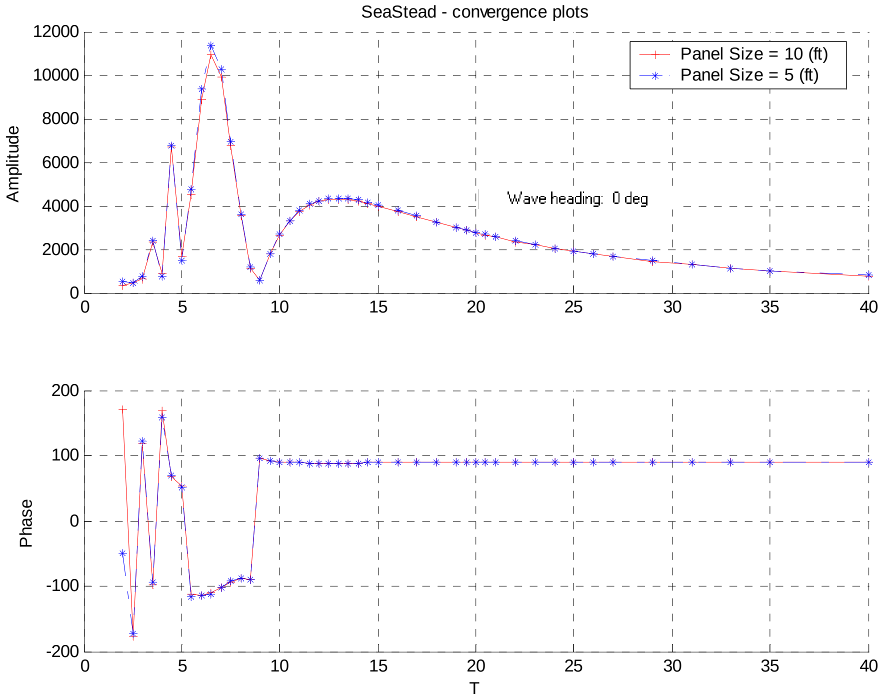


Hydrodynamic coefs in direction 5 5

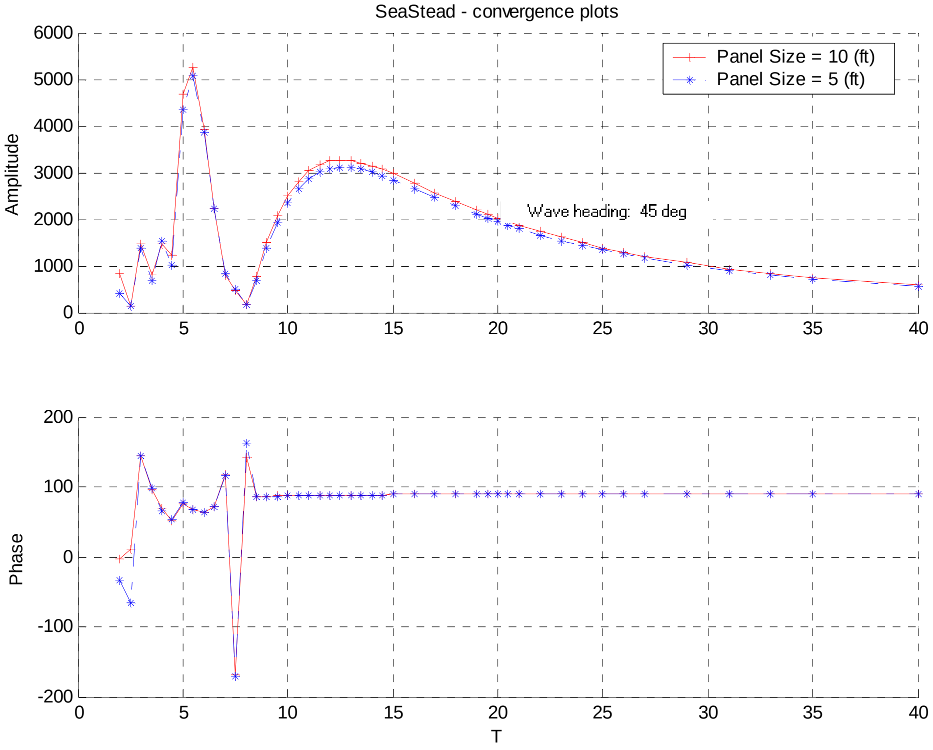


Hydrodynamic coefs in direction 6 6

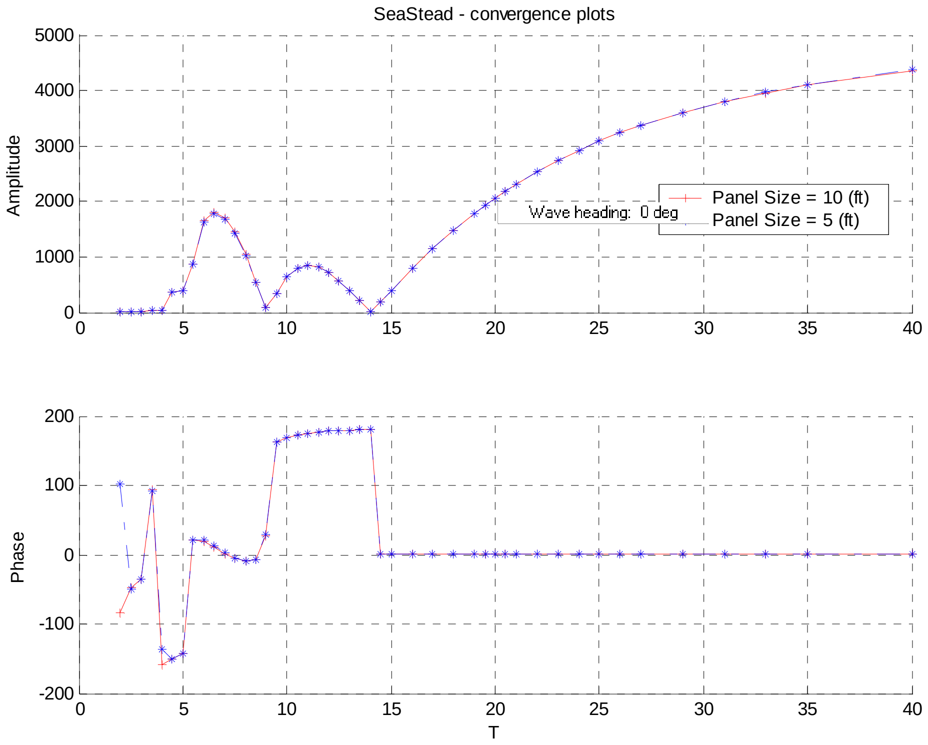
Appendix 2. Diffraction Force Coefficients from WAMIT



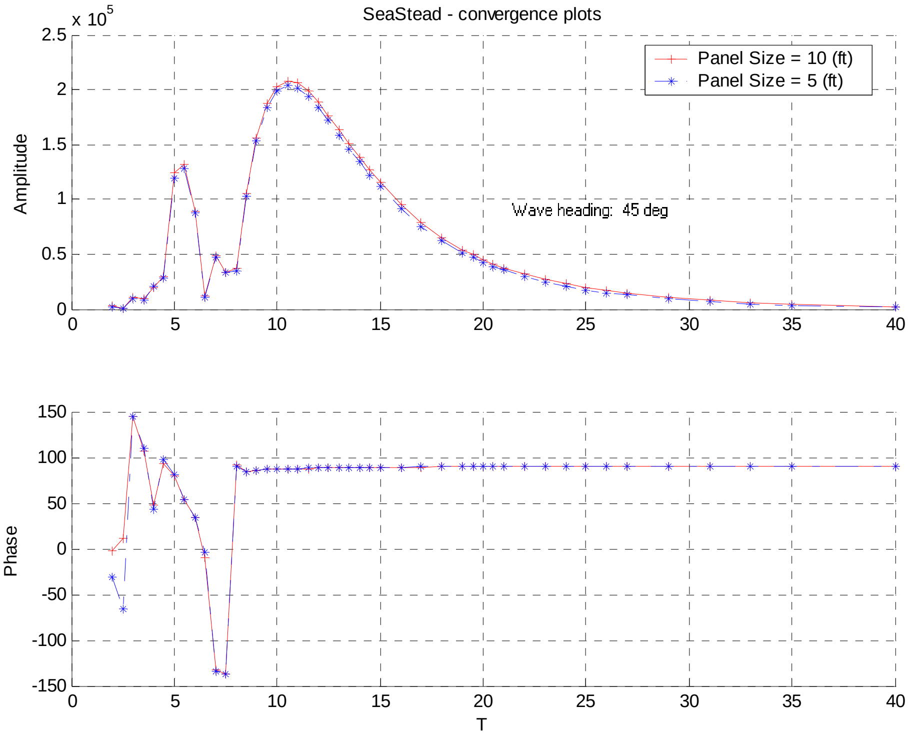
Exciting force in direction 1



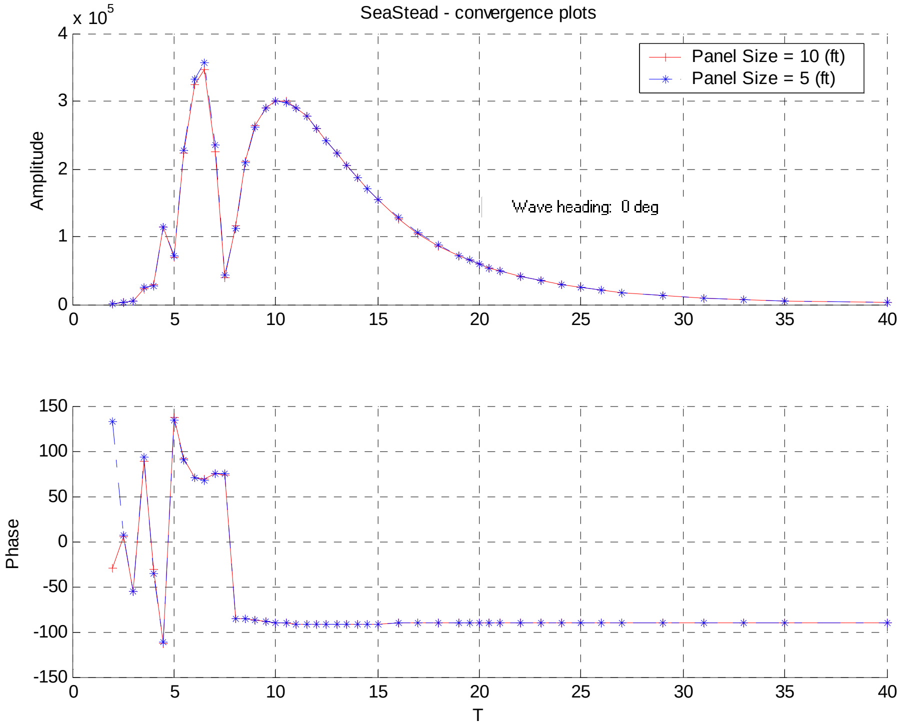
Exciting force in direction 2



Exciting force in direction 3



Exciting force in direction 4



Exciting force in direction 5