

Performance Evaluation of Articulated Multi-body Floaters in Harsh Environment

ABSTRACT

In this paper, the response of articulated floating structures in harsh environment has been investigated. Three applications where articulated joints are used to connect multi-bodies together are considered in this study; namely; VersaBuoy Offshore Platform; VersaBuoy Mobile Offshore Real Estate and the Bottom Feeder System for deck Installation/salvage. The hydrodynamic analyses of the three applications have been performed using both frequency-domain and time-domain approaches. Extensive model test programs are performed to validate the numerical predictions and illustrate the advantage of using the articulated joint to reduce the superstructure motion. Numerical results for the articulated joint loads as well as motion of each component of the multi-body system in comparison to the model test measurements are presented in this paper.

KEY WORDS: multi-body analysis; articulated joint; hydrodynamic interaction; VersaBuoy; Bottom Feeder; floating platforms; mobile offshore real estate; very large floating structures.

INTRODUCTION

Multi-body system could represent the next generation of floating system. In the articulated multi-body system, more than one hydrodynamically interacted hull is used to support a superstructure. This superstructure could be topside of a production or drilling platform, a mobile offshore real estate, floating airports, gantries for deck installation/salvage, etc. These hydrodynamically interacted multi-hulls are connected to the superstructure through articulated joints that allows independent roll/pitch rotation of the hulls relative to the superstructure consuming most of the wave energy as a kinetic energy in the hull motion while allowing only small portion of the wave energy to transmit to the superstructure. This significantly reduces the superstructure motion. The presence of these articulated joints make the system reacts to the applied environmental loads in a fundamentally different manner when compared to the performance of single hull floaters.

In this paper, three examples of articulated multi-body floaters are

presented and the performance in harsh environment has been numerically and experimentally evaluated.

The first example is a VersaBuoy Offshore Platform (OP). The configuration of this floater comprises of four self-stable hulls supporting a typical open truss square deck of dimensions 250 ft x 250 ft. The second example is a VersaBuoy Mobile Offshore Real Estate (MORE) of an area 500 ft x 500 ft supported on 16 hull system while the third application is a Bottom Feeder System (BFS) that consists of two-barges supporting two gantries through four articulated connections.

Multi-body simulations of the VersaBuoy OP (5-body system four of which are hydrodynamically interacting), the VersaBuoy MORE (20-body system 16 of which are hydrodynamically interacting) and the Bottom Feeder BFS (4-body system two of which are hydrodynamically interacting) are performed in both time domain and frequency domain.

Extensive model test programs have been carried out to validate the numerical predictions and confirm the advantages of articulated multi-body performance in harsh environment. Numerical results and comparison with the model test measurements of the system responses are presented in this paper.

THE ARTICULATED JOINT

Articulated connections themselves have formed a staple of automotive and other machine equipment and as such there is a large body of knowledge and experience in their design and specification.

For current applications under consideration the articulated joints transmit an axial thrust of between 1,000 and 2,500 tons and accommodate a range of motion of ± 20 degrees. The joint is located at an elevation of (+) 55 to (+) 60 feet MSL, outside of the splash zone and accessible for regular inspection.

Fig. 1 shows an example of the fabrication of Pin-in-Pin Articulated Joint being manufactured for use in the "Bottom Feeder" custom

salvage system (Fig. 2). The connection has a rated thrust capacity of 2,500 tons and a range of motion of ± 25 degrees. The detail consists of a main pin of 38 inches in diameter and a minor pin of 18 inches in diameter. Lubricated bronze bushing inserts may be used on the wear surfaces as required. Readily available and Industry standard materials can be used for joints with contact stresses in the range of 5 to 10 ksi.

For VersaBuoy floaters, VersaBuoy is proposing an additional safeguard for the articulated connection in the form of a redundant outer articulated joint Fig. 3. Using this arrangement each primary connection can be removed and replaced on an as-needed basis during standard operating conditions.



Fig. 1 Fabrication of Pin-in-Pin Articulated Joint



Fig. 2 Bottom Feeder System in Operation Using Pin-in-Pin Articulated Joints

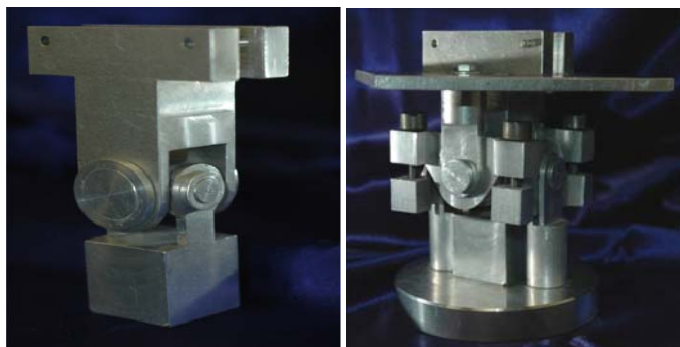


Fig. 3 Articulated Joint; Simple Two Degree-of-Freedom (left) & Redundant Joint (right)

VERSABUOY OFFSHORE PLATFORM

The VersaBuoy Offshore Platform comprises of four spar-like hulls supporting a typical open truss square deck through four articulated

joints. A central well bay in the deck provides SCR and umbilical hang-off locations. Each hull is moored to the seabed by two mooring legs (Fig. 4).

In this application, a deck of 250 feet side dimension is assumed. The system variable load (deck equipment, risers and umbilicals) is 3,125 short tons. A jacket type hull configuration has been chosen for this application (Fig. 5). The hull drafts are set to 397.7 ft. The total platform displacement is 27,440 St and the total required hull steel weight is 5,193 St. A 9,604 St and 6,850 St solid and water ballast are used in this design. The system heave natural period is found to be 27 sec and the pitch/roll natural period is 34 sec. The VersaBuoy OP key figures are summarized in Table 1.

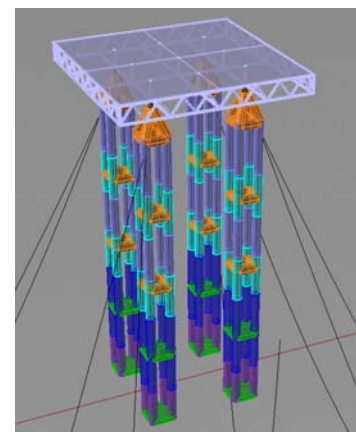
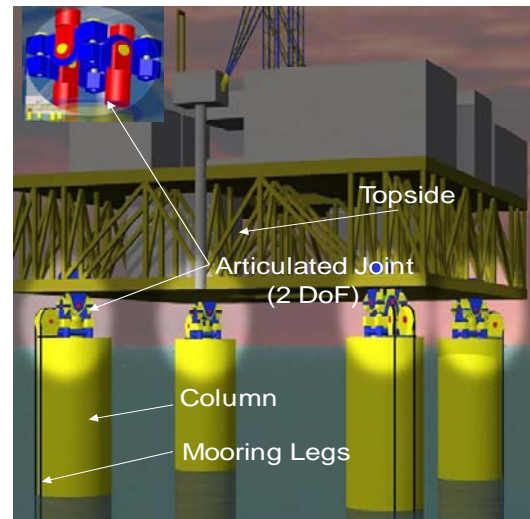


Fig. 4: VersaBuoy Offshore Platform

The four hulls and the deck form a multi-body system composed of 5 bodies four of which are hydrodynamically interacting. The multi-body system has been considered in a three-dimensional hydrodynamic WAMIT simulation. The Higher-Order Method has been used in this WAMIT simulation for body wetted surface discretization. The derived regular panel model from this higher-order discretization for one of the hulls is shown in Fig. 6.

The articulated joints between the bodies are represented by external stiffness matrix which is defined with respect to the body-fixed coordinate system. For a 5-body system, the matrix size is 30x30 since the total degrees of freedom for 5 bodies are 30.

Eigen analysis has been performed to confirm the system stability and predict the system natural periods. Fig. 7 and Fig. 8 show the dominant modes for the deck heave and roll motions with 27.3s and 34.0s deck heave and roll natural periods, respectively. One of the modes with period 134.6s is produced by the coupled roll/pitch motion of the hulls. As it can be seen in Fig. 9 no deck motion is excited in this mode which gives evidence to the decoupling of the hull motion from the deck motion due to the presence of the articulated joints connecting the deck and the hulls.

The VersaBuoy OP configuration considered in this study has been model tested to a scale 1:53 (Fig. 10). Each of the four hulls and the deck has been individually calibrated before the model is assembled in water. Each of the hulls is connected to the deck through an instrumented U-joint that allows the free relative rotation between the hull and the deck in the roll and pitch directions. Tri-axial load cells are used to measure the connection loads between the deck and the hulls. Optical tracking system has been used to monitor the deck six-degree of freedom motion. Three accelerometers are used to measure the deck linear accelerations and derive the angular accelerations of the deck. Wave probs are fitted underneath the deck to measure the airgap.

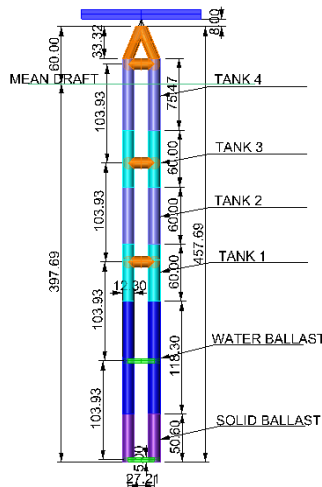


Fig. 5: VersaBuoy OP Jacket Hull Configuration

Table 1: VersaBuoy OP Jacket Hull Configuration

ITEM		Jacket Hull #1
Water Depth	ft	4000
Displacement	St	27,441
Design Draft	ft	397.69
Deck Dimensions (Square: width*height)	ft	250*10
Number of hulls	-	4
Hull Spacing (Center-To-Center)	ft	125.0
Hull Column Diameter (OD)	ft	12.30
Hull Column Height	ft	457.69
Hull Column Spacing C-T-C	ft	27.2
Number of Heave Plates Each Hull		2
Number of Jacket Ring Each Hull	ft	3
Heave Plate/Jacket Ring Vertical Spacing	ft	103.93
Total Topside Payload (Live Load)	St	3,125
Total structure Weight	St	7,862
Solid Ballast Weight	St	9,604
Water Ballast Weight	St	6,850
VCG from Keel	ft	180.6
Heave Natural Period	sec	27

Each hull is moored using mooring line that matches the prototype horizontal mooring stiffness connected to the hulls. Decay tests are performed and confirmed the deck natural periods. Two levels of white noise waves with $H_s = 15$ ft and 30 ft are used to derive the Response Amplitude Operator (RAO) and examine any system nonlinearity. Some regular waves are also applied to confirm the RAO results from the white noise tests.

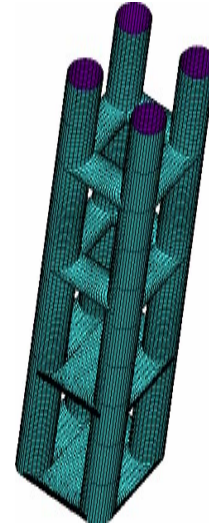


Fig. 6: WAMIT Model of a Jacket Type Hull

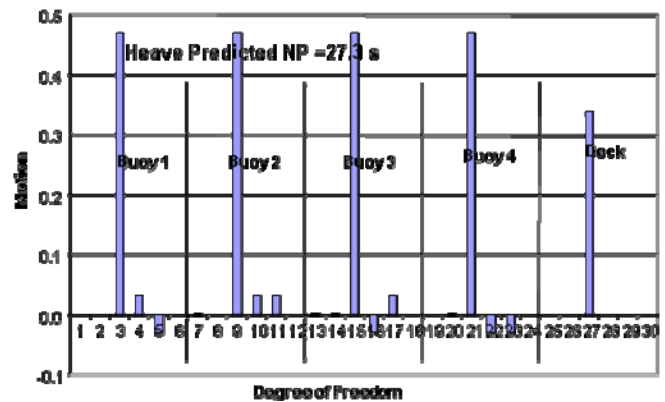


Fig. 73: Deck Heave Motion Dominant Mode

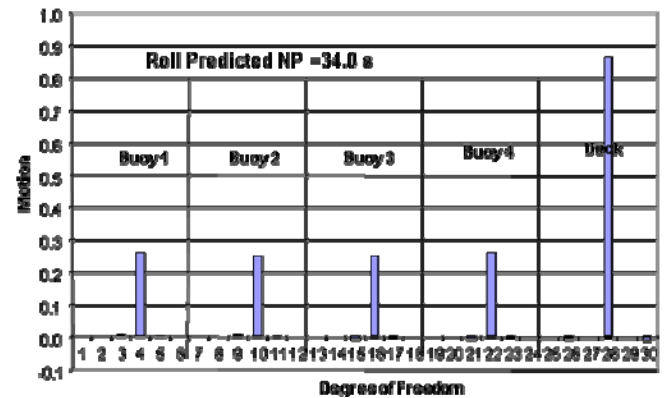


Fig. 8: Deck Roll Motion Dominant Mode

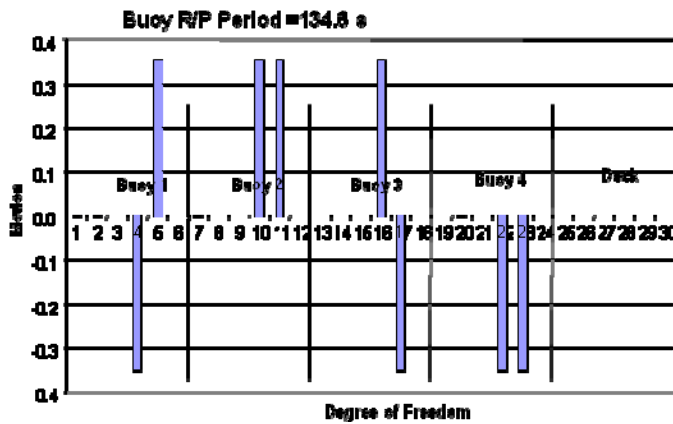


Fig. 9: Hull Roll/Pitch Motion Dominant Mode

The predicted deck motion RAOs from the multi-body simulation has been compared to the corresponding model test derived motion RAOs. Figs. 11~13 show deck surge, heave and roll motion comparisons in quartering seas. Comparison of the hull pitch RAOs is presented in Fig. 14. The articulated joint load RAO comparison is shown in Figs. 15 and 17. It has to be noted that half of the wavelength of a regular wave with 7 s period in deepwater is twice the center to center hull spacing. This explains the peak appears at 7 sec period on the F_y load RAOs (Fig. 16). Very good agreement between the predictions and the model test results has been achieved.



Fig. 10: VersaBuoy Offshore Platform Model Test

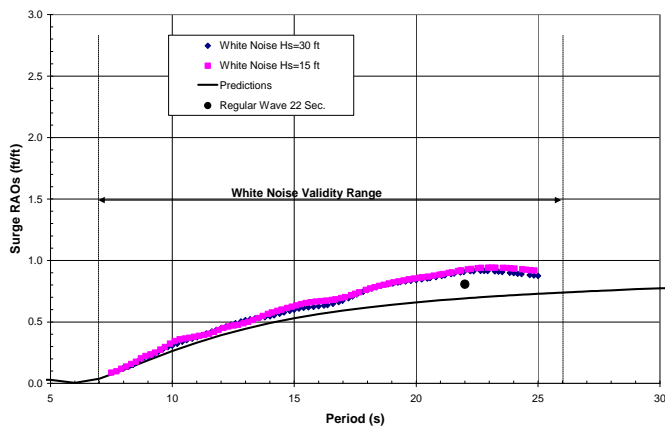


Fig. 11: VersaBuoy Offshore Platform Surge RAOs at Top Deck Level Quartering Seas

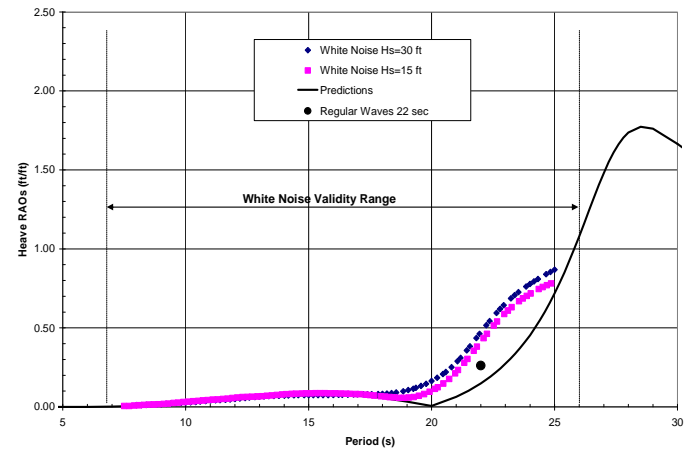


Fig. 12: VersaBuoy Offshore Platform Heave RAOs at Top Deck Level Quartering Seas

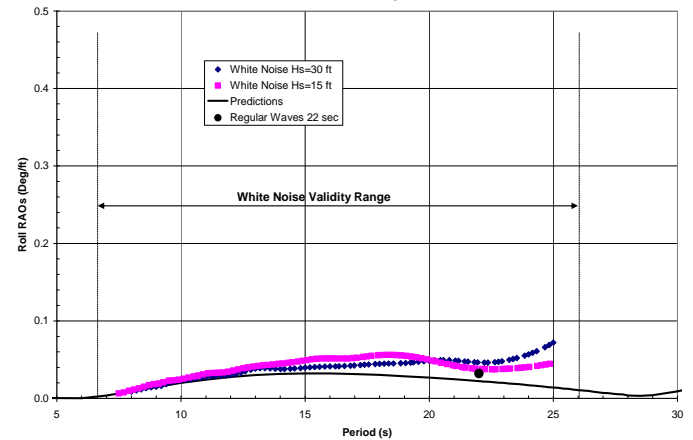


Fig. 13: VersaBuoy Offshore Platform Roll RAOs at Top Deck Level Quartering Seas

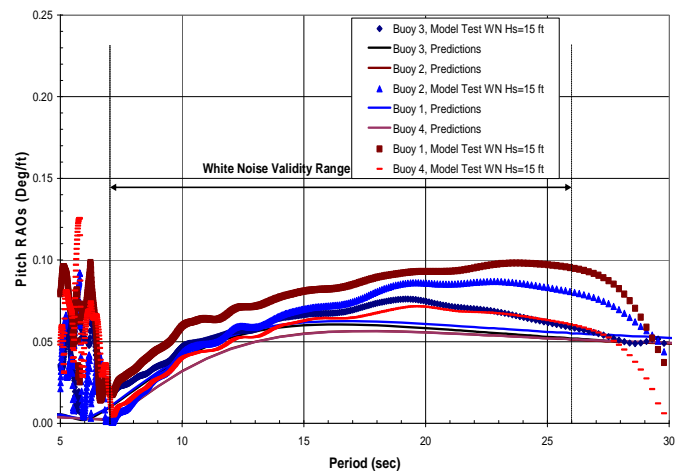


Fig. 14: VersaBuoy Offshore Platform Hull Pitch RAOs Quartering Seas

The model has been tested in 10 year Gulf of Mexico Operating condition with H_s , T_p and γ are 18.8 ft, 10.5 s and 2.0, respectively. The model is also tested in 1000 yr hurricane (H1000) and 100 yr hurricane (H100) extreme events with H_s , T_p and γ are (62.0 ft, 15.5s and 2.2) and (46.0ft, 14.5s and 2.2), respectively.

Deck heave and roll response spectra in H100 event quartering sea are presented in Figs. 18~19. It can be seen on Fig. 18~19 that the wave frequency contribution to the deck motion response is small and the deck motion response is mainly dominated by the second order effect at the natural period. This provides significant benefit to the hull and SCR fatigue design.

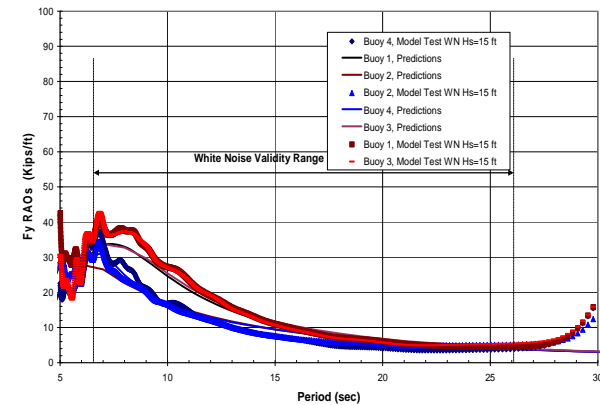


Fig. 15: VersaBuoy Offshore Platform Articulated Joint Fy Load RAOs Quartering Seas

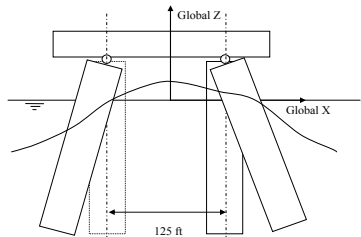


Fig. 16: VersaBuoy Offshore Platform Articulated Joint Fy Load RAOs Quartering Seas

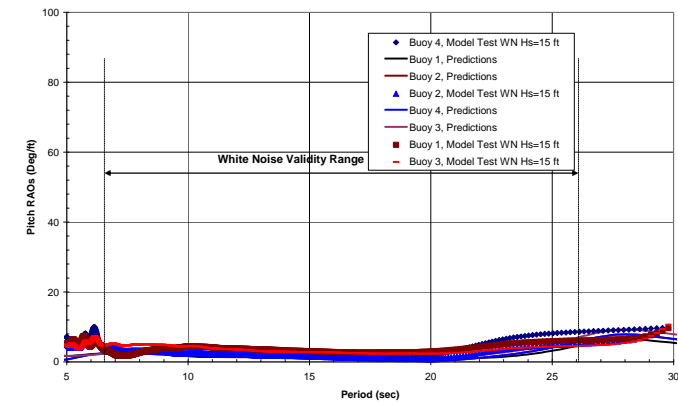


Fig. 17: VersaBuoy Offshore Platform Articulated Joint Fz Load RAOs Quartering Seas

Fig. 20 shows the up-wave hull/deck roll relative motion response spectrum in H100 quartering sea event. As it can be seen that significant amount of energy are exerted by the hull motion and yet not transferred to the deck. The presence of the articulated joints largely helped reducing the amount of wave energy transferred to the deck through decoupling the hull and the deck rotation motion. Under the effect of waves the system is acting as a pendulum with its center at the

keel of the hulls and the articulated joints allow the deck to stay almost horizontal.

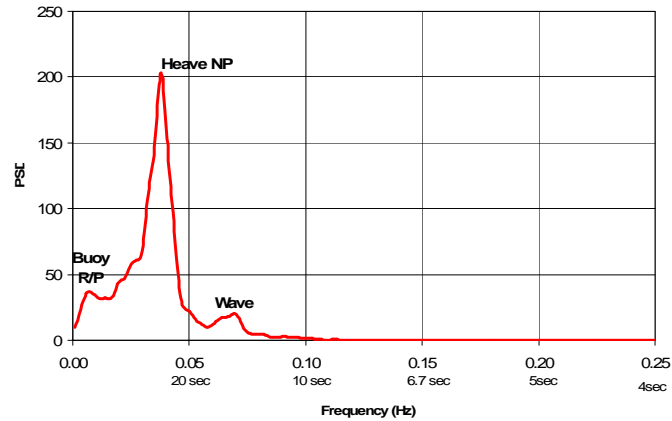


Fig. 18: VersaBuoy Offshore Platform Deck Heave 100-yr Hurricane Response Spectrum – Quartering Sea (Model Test)

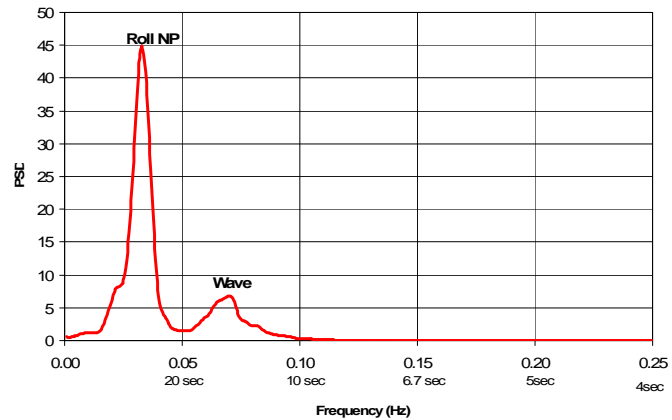


Fig. 19: VersaBuoy Offshore Platform Deck Roll 100-yr Hurricane Response Spectrum – Quartering Sea (Model Test)

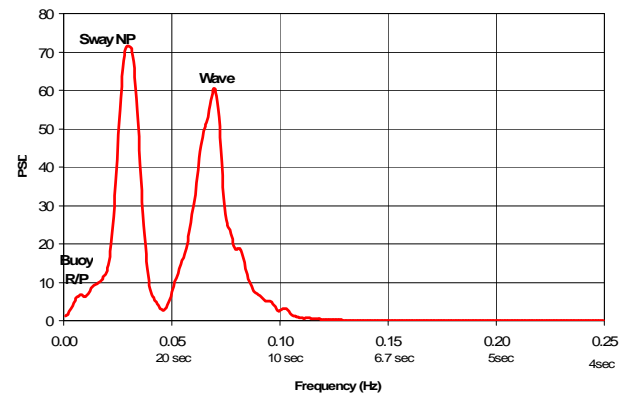


Fig. 20: VersaBuoy Offshore Platform Up-wave Hull/Deck Relative Roll Motion in 100-yr Hurricane Response Spectrum – Quartering Seas

The deck rotation is only produced by the relative heave motion between the up-wave and down-wave hulls. For long wave periods, the up-wave and down-wave hull heave together and produce very small deck rotation while for short wave periods (<7s in this application), the hulls heave with certain phase relationship, however, the contained

energy in these short wave components is small anyway and therefore produces also small deck rotation. The second order roll and heave motions are damping related and can be further reduced by increasing the system damping through additional heave plates if needed.

The articulated joint dominant load component response spectrum in H100 quartering sea event is presented in Fig. 21. It has been found that the articulated joint load is wave frequency dominant and can be accurately predicted by the multi-body linear diffraction simulation. The contribution of the second order effect is negligible.

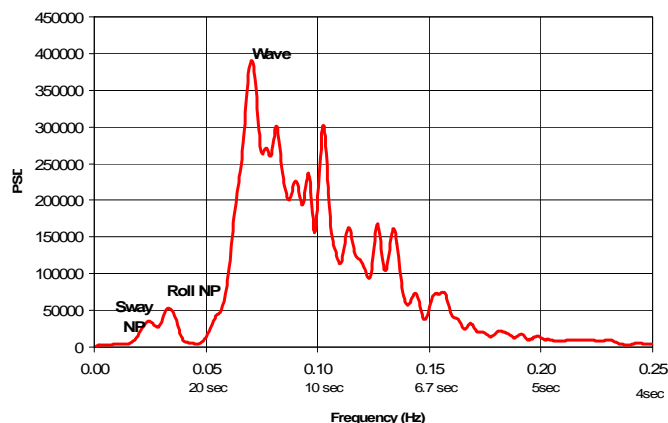


Fig. 21 VersaBuoy Offshore Platform Articulated Joint Load Fx 100-yr Hurricane Response Spectrum – Quartering Sea (Model Test)

Time-domain fully coupled multi-body analysis for the 5-body system has been simulated using AQWA software to further investigate the second order contribution to the design. The AQWA model is presented in Fig. 22. Fig. 23 shows a snapshot of the model in 100-yr hurricane head sea event. It can clearly be seen that hulls independently pitch from the deck and the deck stays almost horizontal under the wave action. The hull also pitches in synchronized motion enabling the system to react to waves as a pendulum.

The deck heave, pitch and surge response spectra in H100 head sea event is shown in Figs 24~26. Very good agreement between model test measurements and AQWA results has been achieved in both wave frequency and low frequency responses. AQWA has slightly under predicted the low frequency hull pitch motion as can be seen in Fig. 27.

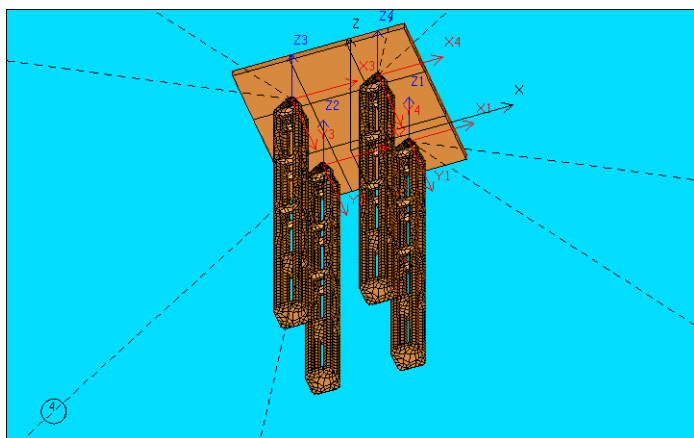


Fig. 22: VersaBuoy Offshore Platform AQWA Model

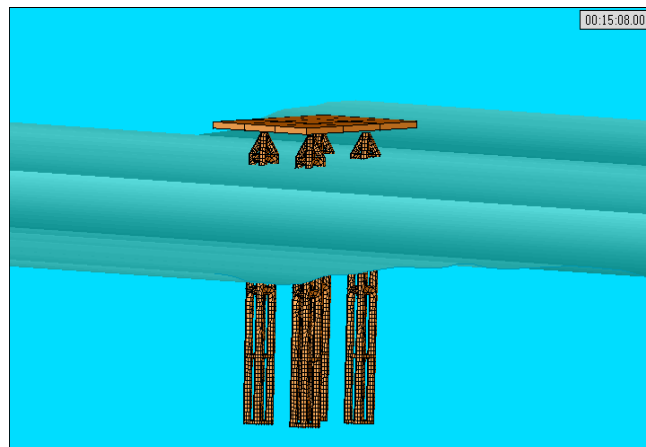


Fig. 23: VersaBuoy Offshore Platform AQWA Model

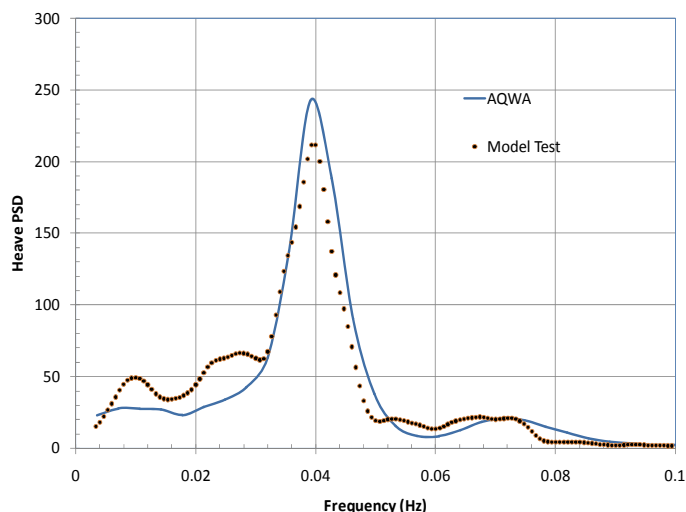


Fig. 24: VersaBuoy Platform Deck Heave 100-yr Hurricane Response Spectrum – Head Sea (Model Test vs. AQWA Simulation)

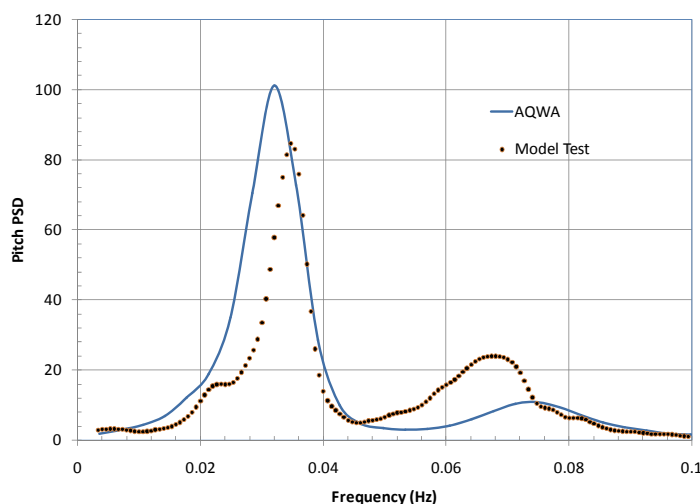


Fig. 25: VersaBuoy Platform Deck Pitch 100-yr Hurricane Response Spectrum – Head Sea (Model Test vs. AQWA Simulation)

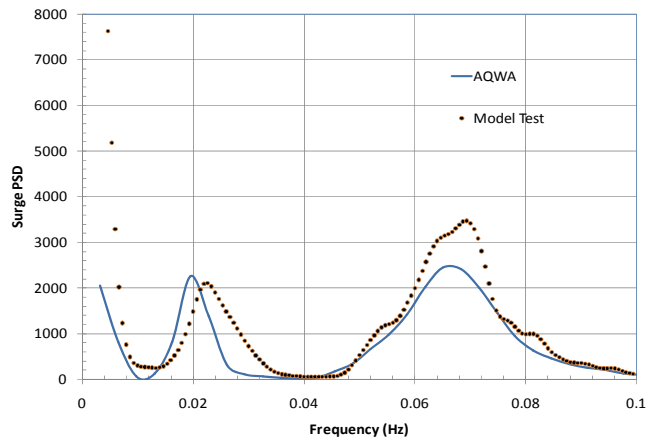


Fig. 26: VersaBuoy Platform Deck Surge 100-yr Hurricane Response Spectrum – Head Sea (Model Test vs. AQWA Simulation)

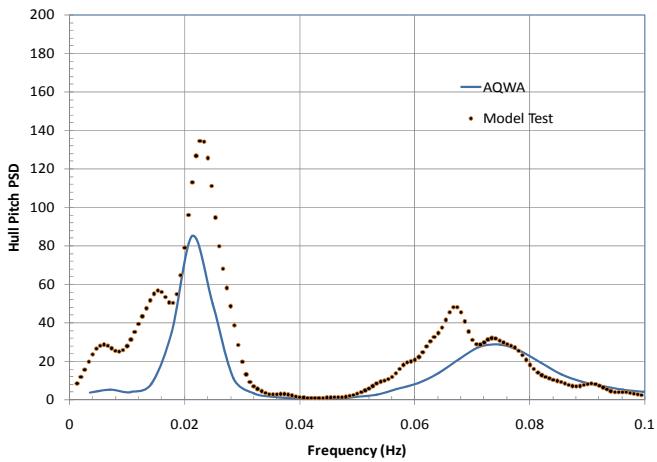


Fig. 27: VersaBuoy Platform Hull Pitch 100-yr Hurricane Response Spectrum – Head Sea (Model Test vs. AQWA Simulation)

The extreme response of the VersaBuoy platform in 10-yr winter storm wave operating condition as well as 1000 and 100 year hurricane events are summarized in Table 2. Excellent performance has been reported in both operating and extreme events. 3.7° and 4.5° maximum roll/pitch deck rotation in 100 and 1000 yr hurricane events are measured. The maximum Fx/Fy articulated load components are 478.0 St and 617.0 St in 100 and 1000 yr hurricane events, respectively.

Table 2: VersaBuoy Offshore Platform Response Summary

Response			10-yr Winter Storm		100-yr Hurricane		1000-yr Hurricane	
			Max.	Min.	Max.	Min.	Max.	Min.
Buoy Load	Fx	kips	369	-404	724	-664	866	-739
	Fy		510	-489	956	-819	1,234	-1,004
	Fz		62	-67	287	-227	299	-243
Buoy/Deck Relative Motion	Roll	deg	1.35	-1.61	6.14	-7.28	9.40	-9.41
	Pitch		1.57	-1.21	6.63	-5.32	9.15	-7.50
Deck Motion	Surge	ft	4.62	-10.40	16.03	-43.10	17.08	-75.84
	Sway		4.07	-10.60	13.93	-47.27	17.49	-75.69
	Heave		0.77	-0.97	8.33	-6.74	14.48	-9.77
	Roll	deg	0.77	-0.79	3.67	-3.26	4.52	-3.68
	Pitch		0.67	-0.46	2.86	-3.66	3.75	-4.23
	Yaw		1.17	-1.81	2.72	-4.11	3.27	-6.61
Deck Acceleration	Surge	g	0.04	-0.05	0.13	-0.13	0.13	-0.14
	Sway		0.05	-0.05	0.14	-0.14	0.15	-0.16
	Heave		0.01	-0.01	0.02	-0.03	0.04	-0.05
	Roll	deg/s²	0.14	-0.18	0.50	-0.53	0.58	-0.55
	Pitch		0.31	-0.30	0.73	-0.82	0.82	-0.92
	Yaw		0.12	-0.11	0.37	-0.32	0.46	-0.39

VERSABUOY MOBILE OFFSHORE REAL ESTATE

The VersaBuoy Mobile Offshore Real Estate (MORE) is the second example presented in this paper of the floaters that use articulated joints to form a multi-body system. The small deck rotation angle experienced by the VersaBuoy Offshore Platform in very harsh environment drove the thought of rigidly connecting the deck of several VersaBuoy floaters together to generate wide multi-purpose land offshore that is suitable for several applications including Mobile Offshore Real Estates (MORE) without encountering extremely high loads at the rigid connections.

A picture of the model test of four VersaBuoy floaters rigidly connected together in a 2 x 2 arrangement to form a deck area of 500 ft x 500 ft is shown in Fig. 28.

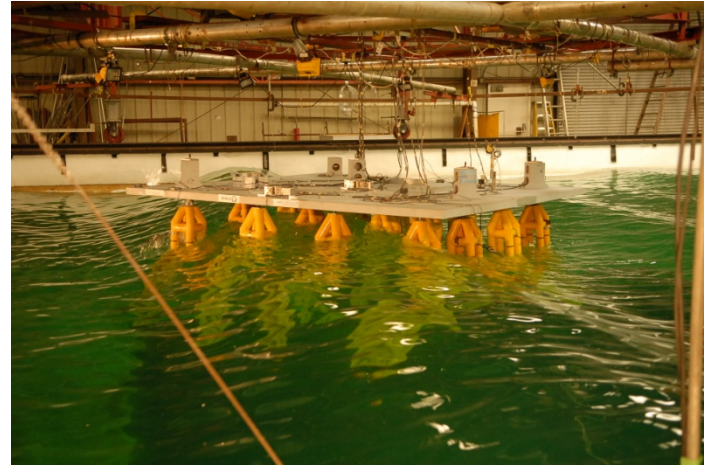


Fig. 28: VersaBuoy MORE Model Test

The twenty-multi-body system has been simulated using WAMIT software with higher order boundary element method. Excellent agreement with the model test measurements has again been achieved. The comparison between the predicted and measured deck/deck connection force Fx and Moment My RAOs is shown in Figs. 29~30.

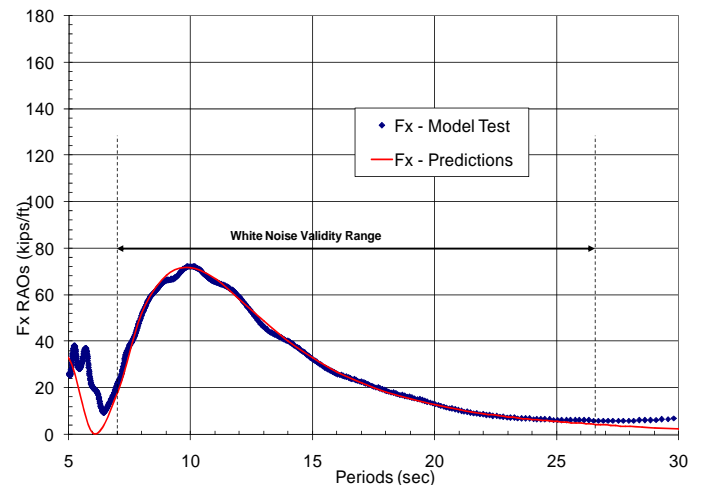


Fig. 29: VersaBuoy MORE Deck/Deck Load Fx RAOs – Quartering Sea (Model Test vs. WAMIT Simulation)

The 100-year hurricane deck/deck connection loads response spectra in quartering seas are presented in Figs. 31~32. The connection loads was founded to be wave frequency dominated.

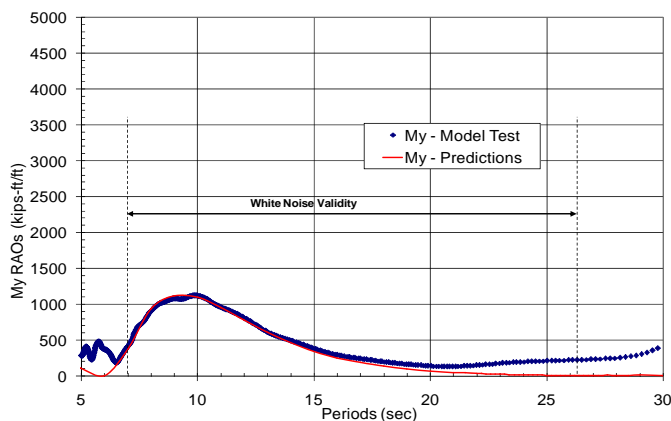


Fig. 30: VersaBuoy MORE Deck/Deck Moment My RAOs – Quartering Sea (Model Test vs. WAMIT Simulation)

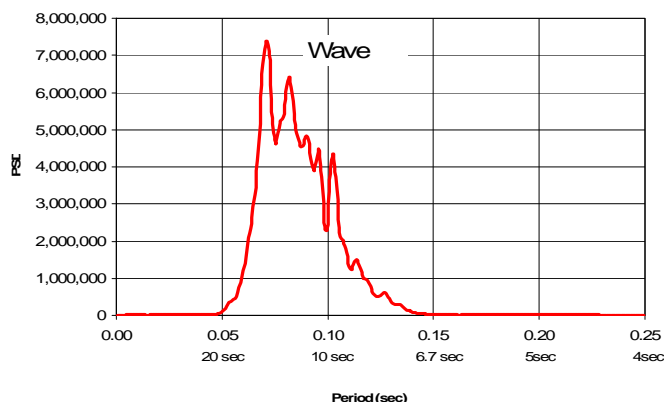


Fig. 31: VersaBuoy MORE Deck/Deck Connection Load Fx 100-yr Hurricane Response Spectrum – Quartering Sea (Model Test)

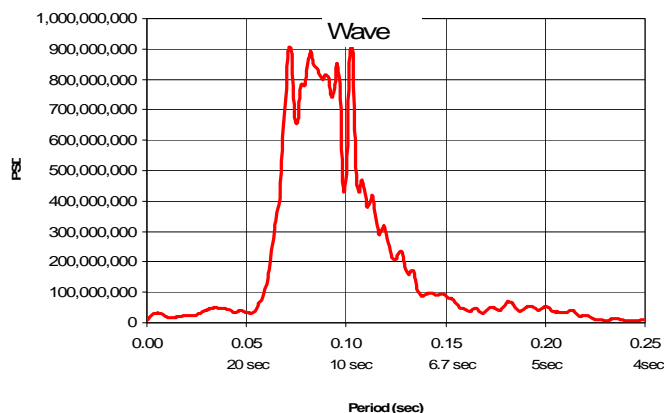


Fig. 32: VersaBuoy MORE Deck/Deck Connection Moment My 100-yr Hurricane Response Spectrum – Quartering Sea (Model Test)

Table 3 summarizes the maximum responses for the VersaBuoy MORE in 10 yr winter storm and 100 and 1000 yr hurricane events. The maximum roll/pitch angle is found to be 1.3° and 2.3° in 100-yr and 1000 yr hurricane events, respectively. The hull relative pitch/roll angle w.r.t deck is 8.0° and 10.5° for 100-yr and 1000-yr, respectively. This affirms the articulated joint merit to allow only small motion for the topside and have the rest of the wave energy dissipated in producing motion to the hulls. The deck/deck rigid connection loads are found to be within a practical design limits where the Fx/Fy is in the order of

1150 St and 1000St in 1000 and 100 yr hurricane events, respectively. The maximum moments Mx/My are 30,185 St-ft and 26,780 St-ft in 1000 and 100 yr hurricane events.

Table 3: VersaBuoy MORE Response Summary

Response			10-yr Winter Storm		100-yr Hurricane		1000-yr Hurricane	
			Max.	Min.	Max.	Min.	Max.	Min.
Buoy Load	Fx	kips	466	-464	1,141	-825	1,309	-1,257
	Fy		509	-513	1,192	-921	1,586	-1,516
	Fz		155	-162	394	-408	381	-489
Buoy/Deck relative Motion	Roll	deg	1.00	-0.94	7.78	-3.64	10.64	-5.37
	Pitch		1.12	-0.98	8.83	-3.78	11.88	-5.47
Deck Motion	Surge	ft	3.31	-8.11	12.12	-40.56	16.71	-62.74
	Sway		3.02	-7.81	11.85	-38.52	16.71	-60.94
	Heave		0.45	-1.09	5.57	-3.12	10.61	-8.01
	Roll	deg	0.22	-0.41	1.15	-1.24	1.89	-2.12
	Pitch		0.28	-0.21	1.30	-1.29	2.05	-2.00
	Yaw		0.34	-0.23	0.52	-0.43	1.04	-0.56
Deck Acceleration	Surge	g	0.01	-0.02	0.06	-0.07	0.08	-0.09
	Sway		0.02	-0.01	0.07	-0.07	0.10	-0.08
	Heave		0.01	-0.01	0.02	-0.03	0.04	-0.04
	Roll	deg/s^2	0.09	-0.11	0.24	-0.22	0.28	-0.30
	Pitch		0.15	-0.13	0.48	-0.43	0.58	-0.51
	Yaw		0.12	-0.16	0.15	-0.25	0.19	-0.33
Force b/w Decks Face 1	Load FX	kips	959	-956	1,969	-1,987	2,167	-2,336
	Load FY		390	-378	923	-1,196	1,116	-1,403
	Load FZ		111	-101	287	-134	381	-192
	LoadMxx	kips-ft	20,783	-20,836	53,572	-36,885	60,377	-44,996
	LoadMyy		9,985	-9,110	18,573	-23,184	23,052	-23,622
	LoadMzz		21,659	-19,249	28,496	-38,800	36,858	-32,291
Force b/w Decks Face 2	Load FX	kips	298	-344	954	-838	1,159	-968
	Load FY		841	-842	1,624	-1,752	2,052	-2,011
	Load FZ		91	-96	120	-240	173	-301
	LoadMxx	kips-ft	7,968	-7,537	16,856	-19,569	23,261	-23,066
	LoadMyy		16,738	-16,787	40,849	-28,862	49,233	-34,665
	LoadMzz		17,955	-14,661	27,398	-79,677	42,394	-87,249

BOTTOM FEEDER SYSTEM

The third example that uses articulated joints is the Bottom Feeder System BFS, (Fig. 2). This system is used for deck salvage and installation. It can also be used for pile installation.

The system consists of two identical barges carrying two transverse gantries with a single articulated joint connection that allows roll/pitch relative rotation between the barge and the gantry at one end and four articulated joint connections at the other end which only allows relative roll rotation of the barge relative to the gantry. The connection arrangement with respect to the barges is reversed for the other gantry.

Allowing the rotation of the barges relative to the gantries again dissipate the wave energy away from the gantries and keep the gantries almost stationary for the installation/salvage operating seastates.

The system comprises of four bodies two of which are hydrodynamically interacting.

WAMIT software has again been used to predict the multi-body system motion. WAMIT model is presented in Fig. 33. Two cases have been considered; transport case in 20 ft significant wave height (Fig. 34) and 4000 St deck lift case in 8 ft significant wave height (Fig. 35).

Model testing has been performed to verify the predicted response from the multi-body simulation. Model test instrumentations are shown in Fig. 36. Very good agreement between the measurements and the multi-body simulations has been achieved. Sample comparisons are shown in Figs. 37~38. It has to be noted that the RAOs from the model in Figs. 37~38 are not reliable at the low and high wave periods since it is derived from the wave spectrum where small energy are present.

Comparison of the extreme motion responses of the gantries and the barges shows that the barges roll 17.7° and 7.7° while the gantries roll

only 8.9° and 4.1° in the transport and deck lift cases, respectively. Thanks largely due to the articulated joint.

The maximum lateral load components on the articulated joints are 315 St and 235 St in the transport and lift cases, respectively. The corresponding numbers in the vertical direction are 105 St and 950 St, respectively. The maximum M_z moment does not exceed 10,000 St-ft in any of the two cases. The articulated joint loads stayed within a practical designable level.

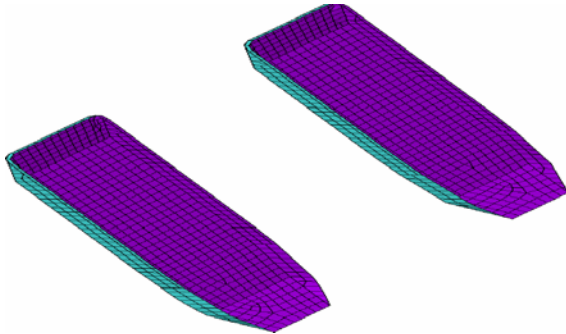


Fig. 33: Bottom Feeder WAMIT Model



Fig. 34: Bottom Feeder Transport Condition

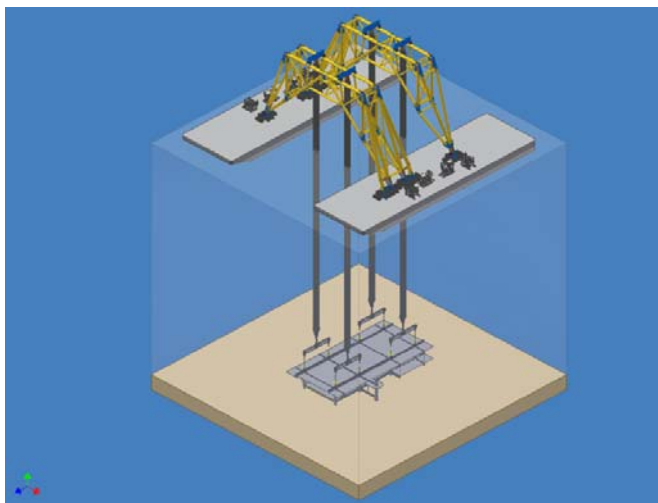


Fig. 35: Bottom Feeder 4000 St Deck Lift Condition

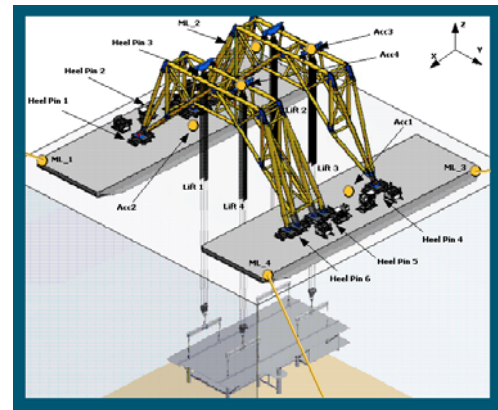


Fig. 35: Bottom Feeder Model Test Instrumentations

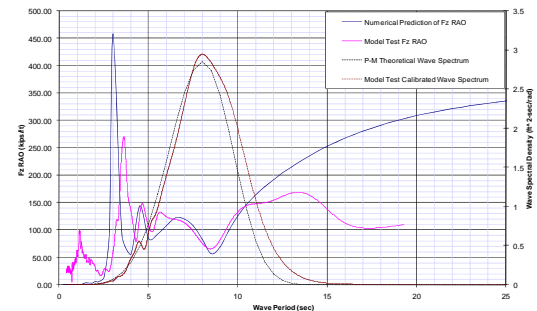


Fig. 36: Bottom Feeder Articulated Joint Fz RAOs (Model Test vs. Predictions)

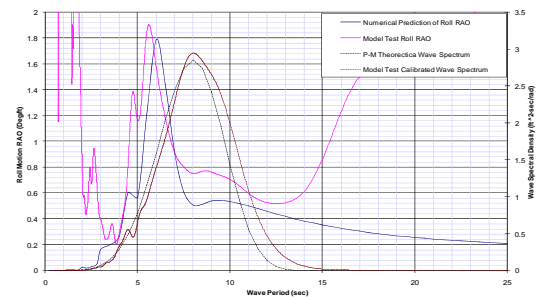


Fig. 37 Bottom Feeder Barge Roll Motion RAOs (Model Test vs. Predictions)

CONCLUSIONS

The performance of types of articulated structures, namely; VersaBuoy OP, VersaBuoy MORE and Bottom Feeder BFS, has been extensively numerically and experimentally examined in harsh environment. In each of these structures, articulated joints are used to connect a superstructure to multi-hull system. Numerical results from the state-of-the-art multi-body simulations in both frequency domain and time domain have been experimentally verified. The introduction of the articulated joints has been proven to significantly reduce the superstructure motions while experiencing loads within the practical designable levels and opens door for a new generation of floaters.

REFERENCES

WAMIT User Manual Version 6.1s, 2002.
AQWA Reference Manual – Version 5.7B, 2006.