Responses of a Tanker-Based FPSO to Hurricanes in the Gulf of Mexico

by

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Abstract

A series of model tests were completed in the Offshore Technology Research Center wave basin to investigate the responses of a tanker-based FPSO to hurricane environments. Results indicate that transverse responses, particularly roll, are significantly influenced by non-parallel environments and directional seas.

Introduction

While FPSO's have successfully used in many other areas worldwide, none have been used to date in the Gulf of Mexico. With increasing interest in their use in the Gulf, model tests were conducted at the Offshore Technology Research Center wave basin to examine the behavior of FPSO's in wave, wind, and current conditions typical of the passage of a severe hurricane. FPSO's for the Gulf of Mexico will likely be passively moored through a turret system so that the tankers can weathervane or rotate in response to the changing wave, wind, and current directions in a hurricane.

In many areas where FPSO's have been used, the wind, wave and current conditions are relatively parallel or collinear. In such an environment, the FPSO is generally subjected to head seas. The typical design practice for such FPSO's assumes that the design wave, wind, and currents are parallel. The waves are assumed to be unidirectional or long-crested.

However waves, winds, and currents in a hurricane can be quite non-parallel [1], and subject the vessel to quartering or beam seas that can significantly influence the response of a ship-shaped vessel. For example, conditions that result in quartering or beam seas can cause larger roll amplitudes than that would result from head seas. The extreme responses of a moored FPSO can be sensitive to non-parallel waves, winds, and currents. The extreme or design responses of an FPSO is recognized to be sensitive to non-parallel waves, wind, and currents [1, 2], but few studies have addressed this issue.

A recent study investigated response based design criteria for FPSO's in the Gulf of Mexico [3]. A frequency domain analytical model was used to predict the responses of an FPSO from hindcast hurricane waves, winds, and currents that were generally non-parallel. The effect of directional waves was approximated in the model. Results showed larger than anticipated roll that was due in part to quartering to beam seas that can result from non-parallel waves, winds, and currents, and in part to directional seas.

Roll that was larger than expected has also been observed on operating FPSO's [4].

The model tests described here were designed and conducted to examine the responses of an FPSO in non-parallel wave, wind, and current conditions and wave directionality (i.e., short-crested waves) typical in the passage of a severe Gulf of Mexico hurricane. Results from these tests can be used to assess the importance of realistic descriptions of hurricane wave, wind, and current conditions on the simplifying assumptions often used in design practice.

Wave Basin

The OTRC wave basin, located at Texas A&M University, is a world-class facility that is used to conduct tests in support of research to develop new technology and to conduct tests to validate designs for new deepwater structures designed for the Gulf of Mexico and elsewhere. Many of the deepwater structures that have been designed and installed in the Gulf have been tested at the OTRC.

The OTRC wave basin was well suited to generate the non-parallel environments and the short-crested waves required for this study. The basin is 100 ft wide x 150 ft long, has a water depth of 19 ft, and has a deep pit (30 ft long x 15 ft wide x 55 ft deep) in the center of the basin (Figure 1). The segmented wave generator can produce regular and irregular unidirectional waves as well as short-crested multidirectional seas. Wind is generated by an array of 16 variable speed fans. Currents are generated by pumping large volumes of water through manifolds of high velocity jets that generate currents in the basin by entrainment. The current generator manifolds and wind fans can be located in the basin so as to generate non-parallel waves, winds, and currents. These capabilities allow the generation of non-parallel waves, winds, and currents and short-crested multidirectional seas that can realistically simulate the severe conditions in a hurricane. Figure 2 shows the OTRC basin set up for such a test.

Test Program

The test program focused on different descriptions of the wave, wind, and current (WWC) environment representing a 100-year Gulf of Mexico wave condition near the eye of a severe hurricane (see Figure 3). Associated winds and currents were modeled for the non-parallel and parallel cases. Multidirectional waves for three spreading factors S [$\cos2S(\theta)$ spreading model] were run without winds or currents. Note that the multidirectional waves are spread the most for the small values of S and approach unidirectional for large values of S. See Table 1 and Figure 4.

The environment that created the maximum roll in the study by Baar et al [5] was also tested. This environment could occur in the left real quarter of a hurricane far away from the eye (see Figure 3). Note that the wind was blowing about -80 degrees from the waves, creating quartering to beam seas. See Table 1 and Figure 4.

We also tested environments representing the 1000-year hurricane wave condition and associated winds and currents (parallel WWC) and a 10-year winter storm wave environment, as shown in Table 1.

A JONSWAP spectrum was used to simulate the waves. A peak enhancement factor was 2.5 was used for the 100-year conditions and 1.4 for the maximum roll conditions. Waves were calibrated in the presence of and currents. Wind gustiness was modeled using the NPD spectrum.

Each test simulated the indicated environment for 3 hours (prototype time scale).

FPSO Model

The FPSO model tested for this study is a 200,000 DWT tanker moored in 6,000-ft water depth using a taut polyester mooring system. The FPSO has a length between perpendiculars of 1017 ft, is 154.8 ft wide and 92 ft deep with a full-load draft of 62 ft. The draft during the test was 46.5-ft draft representing 75 percent of the full-load draft. The model scale was 1:60 resulting in a model that was about 17 feet long. The FPSO model is shown in Figure 5-7 and during testing in Figures 8-9.

The 4x3 prototype mooring system was modeled as an equivalent 4x1 system shown in Figure 10 The mooring lines for the model were truncated to accommodate the 1:60 scale of the FPSO model in the wave basin, and were designed to simulate the static force-displacement characteristics of the prototype system. The force-displacement characteristics for the prototype mooring system are shown in Figure 11, and the results shown indicate good agreement between the prototype and the model.

The measured natural periods and damping (calm water) of the FPSO are shown in Table 2

Measured FPSO responses included motions (6 degrees-of-freedom), mooring line tensions, forces (X,Y,Z) on the turret, accelerations (X,Y,Z) at the turret location, and wave overtopping at six locations along the hull. The wave, wind, and current conditions were also measured.

Results

The FPSO response statistics measured in the various tests are shown in Table 3. The “maximum” refers to the maximum value measured in the 3-hour simulation. The “range” is the magnitude of the difference between the maximum and minimum values in the 3-hour simulation.

Figures 12-16 compare response statistics for surge, sway, mooring line tension, yaw, and roll for the different 100-year non-parallel and parallel WWC cases, the 100-year directional wave cases, and the non-parallel WWC case expected to cause maximum roll.

Surge Figure 12 presents the results for surge. The maximum and mean surges are larger for the 100-year non-parallel and parallel WWC cases as expected. The lower surge for the Maximum Roll WWC case reflects the lower waves and winds. The surges for the 100-year directional waves are smaller than the 100-year non-parallel and parallel WWC cases, and show little variation with spreading factor.

The measured time series and the corresponding spectrum for surge in the non-parallel 100-year environment are shown in Figure 17. The spectral peak period of the surge is 210 seconds, confirming that most of the FPSO's dynamic surge response is at its surge natural period (206 sec) and there is no surge response at the wave frequencies.

Sway Figure 13 presents the results for sway. The means and standard deviations are generally small and similar for all cases. The range is large the two non-parallel WWC cases, likely reflecting the influence of the winds at angle to the waves. The similar value for the 100-year non-parallel and the Maximum Roll cases is merely fortuitous. The sway for the 100-year parallel WWC is much smaller than for the non-parallel cases.

The ranges in the sway for the 100-year directional waves are similar for the three spreading factors, and are as large as the two non-parallel WWC cases. The means and standard deviations are again generally small and similar for all spreading factors. The large range and small standard deviations are again suggestive of a highly nonlinear process

Mooring Line Tension Figure 14 presents the results for the tension in mooring line number 2. The trends are similar to those noted for the surge (Figure 12). The maximum and mean line tensions are larger for the 100-year non-parallel and parallel WWC cases as expected. The line tensions for the 100-year directional waves are slightly smaller than the 100-year parallel WWC case, and show little variation with spreading factor.

The maximum and mean tensions for the Maximum Roll case are similar to those for the 100-year parallel WWC case. Recalling that the waves are significantly lower for the Maximum Roll case, the similarities in line tension is fortuitous and results from the larger loads on the highly yawed FPSO.

The measured time series and the corresponding spectrum for line tension in the 100-year non-parallel WWC environment are shown in Figure 18. The peak spectral period of line tension is 209 seconds, confirming that the tension dynamics are principally due to FPSO surge, and there is minimal surge response at wave frequencies or contributions from surge or pitch.

Yaw Figure 15 presents the results for yaw. The values for the mean and the range for yaw for the two non-parallel WWC cases were large. The mean was –20 degrees for the non-parallel 100-year WWC case and +40 degrees for the Maximum Roll case, reflecting the influence of the angles between the wind and the waves. Figure 19 shows the coherence between waves and yaw and Figure 20 shows the coherence between wind and yaw for the non-parallel 100-year WWC conditions. These figures confirm the yaw is governed by the wind for this non-parallel environment. The yaw for the parallel 100-year WWC case was small as would be expected.

The ranges in the yaw in the 100-year directional waves were also large. The mean values are small, as would be expected, as there are no winds or currents. The standard deviations are also small. The large range and small standard deviations are suggestive of a highly nonlinear process.

Roll Figure 16 presents the results for roll. The rolls for the 100-year non-parallel and parallel wave, wind, and current (WWC) cases are similar. The means and standard deviations are nearly the same – the difference is the 3-hour maxima are likely reflects the statistical variability in measured extremes.

The roll in the 100-year directional waves is surprisingly large. Both the standard deviation and the maxima are significantly higher than the than the two 100-year WWC cases. Recall that the waves are unidirectional in the WWC cases. As the mean yaws are less than 10 degrees (Figure 15), the large rolls appear to be due to the multidirectional nature of these short crested seas. The standard deviations are nearly constant for all spreading factors, but the trend in maximum values suggests that the maximum roll is larger in more spread seas. While this seems logical and appealing, the statistical variability in the measured 3-hour maxima could also play a role in this observed trend.
The roll in the Maximum Roll case is also higher than the two 100-year WWC cases. Recall that the winds were at 80 degrees to the waves and currents. This resulted in the large yaw angles (Figure 15), and subjected the FPSO to quartering waves.

Heave and Pitch Results for heave and pitch (not shown) vary little for the different realizations of the 100-year conditions.

Summary & Conclusions

Non-parallel waves, wind, and currents were used to model realistic hurricane environments representing different positions of a hurricane as it passed the moored FPSO. Directional wave spectra were also used to realistically model the effects of wave spreading due to multidirectional storm seas. Other environments were also modeled to examine the impact of simpler specifications of waves, winds, and currents often used in design practices. Results were compared to assess the importance of realistic descriptions of hurricane wave, wind, and current conditions on simplifying assumptions often used in FPSO design practice.

Table 4 providesa simple summary of the results of this experimental study. Measured responses in parallel WWC environments are not always larger than responses in more realistic environments, e.g., non-parallel WWC or directional seas that are typical in hurricanes in the Gulf of Mexico. This suggests that simplified design methods based on parallel WWC can underpredict certain FPSO responses that are important in design.

The results indicate that the transverse responses particularly roll, are significantly influenced by non-parallel WWC environments and directional seas. These results suggest that the design of FPSO’s for hurricanes should incorporate realistic descriptions of the complete hurricane environment in the design procedures and model tests to validate the design performance. The results also indicate the importance of wave directionality and multidirectional seas on FPSO roll, and may explain some of the observed rolls that have been larger than expected. These results in general confirm many of the trends noted in the analytical study by Baar et al [5].

Results from these tests have been compared to predictions from a coupled dynamic analysis model developed by Kim [6] to predict the global responses of an FPSO. The numerically predicted global vessel motions are in reasonable agreement with the measurements.
Further wave basin testing is also planned to better understand the complex responses of FPSO’s, to better assess the importance of these complexities and realistic descriptions of hurricane wave,

wind, and current conditions on responses of importance in design, and to validate FPSO design tools and practices.

Acknowledgements

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Table 1: Wave, Wind, and Current Test Conditions

Environment	Wave			Wind		Current	
	Significant Height (ft)	Peak Spectral Period (sec)	Spreading Factor S	Speed (mph)	Direction (degrees from wave)	Speed (fps)	Direction (degrees from wave)
100-Year							
Non-Parallel WWC	40	14	-	92	+30	3.0	-30
Parallel WWC	40	14	-	92	0	3.0	0
Multidirectional S=2	40	14	2	0	-	0	-
Multidirectional S=4	40	14	4	0	-	0	-
Multidirectional S=6	40	14	6	0	-	0	-
Unidirectional Wave Only	40	14					
Maximum Roll							
Non-Parallel WWC	27	14	-	60	-80	3.5	0
1000-Year							
Parallel WWC	47	15	-	96	0	6.9	0
10-Year							
Unidirectional Wave Only	20	9	-	0	-	0	-

Table 2: Measured Natural Periods and Damping

Mode	Period (sec)	Damping (%)
Pitch	10.5	16.5
Roll	12.7	4.4
Heave	10.7	13.9
Surge	206.8	3.0

Table 3: FPSO Response Statistics - OTRC Wave Basin Tests

Response	Statistic	100-Year Hurricane					Max. Roll	1000-Year	10-Year	100-Year
		Non-Parallel	Parallel	Directional				Parallel		
				s=2	s=4	s=6				
		WWC	WWC	Wave Only	Wave Only	Wave Only	WWC	WWC	Wave Only	Wave Only
Surge (ft)	Max.	8	15	68	32	42	25	-12	19	28
	Min.	-201	-180	-141	-136	-129	-105	-242	-61	-130
	Max Absolute	201	180	141	136	129	105	242	61	130
	Mean	-75	-80	-39	-39	-38	-36	-116	-19	-39
	Mean Absolute	75	80	39	39	38	36	116	19	39
	Stnd. Dev	32	33	26	26	29	20	34	14	25
Sway ft)	Max.	42.9	31.9	60.2	73.2	62.1	33.0	62.6	16.0	22.6
	Min.	-70.3	-18.4	-52.2	-46.3	-45.7	-58.5	-24.2	-4.6	-12.6
	Range	113.2	50.3	112.4	119.5	107.8	91.5	86.8	20.6	
	Mean	-0.3	8.5	3.5	5.1	3.7	-11.2	11.1	5.1	3.5
	Stnd. Dev	15.0	7.6	18.2	16.3	15.0	16.4	11.7	2.9	5.0
Yaw (deg)	Max.	-3.4	4.7	24.9	21.0	25.4	56.8	11.2	4.5	
	Min.	-24.6	-5.6	-14.1	-14.8	-0.4	23.7	-5.7	-7.7	
	Range	21.2	10.3	39.0	35.8	25.8	33.1	16.9	12.2	
	Mean	-16.0	-0.3	0.6	1.4	9.8	40.7	1.0	-0.8	
	Stnd. Dev	3.8	1.8	7.0	6.7	5.3	6.9	2.6	2.1	
Mooring Line 1 (kip)	Max.	2329	1729	1616	1553	1564	1537	2117	1210	1631.0
	Min.	827	789	611	633	721	778	856	839	726.0
	Mean	1322	1252	1086	1067	1069	1161	1399	1008	1116.0
	Stnd. Dev	186	149	139	128	129	128	158	61	129.0
Mooring Line 2 (kip)	Max.	1827	1923	1335	1269	1196	1512	2314	1096	1598.0
	Min.	658	772	382	450	406	667	968	735	729.0
	Mean	1259	1315	835	835	839	1007	1488	928	1098.0
	Stnd. Dev	180	167	128	119	119	123	193	58	126.0
Roll (deg)	Max.	3.5	2.0	9.3	7.5	6.9	5.3	3.9	0.9	2.1
	Min.	-3.6	-2.0	-7.9	-7.0	-7.7	-5.1	-4.1	-0.7	-2.0
	Mean	-0.1	0.0	0.2	0.1	0.1	0.1	0.0	0.1	0.0
	Stnd. Dev	0.9	0.6	2.4	2.4	2.1	1.2	0.9	0.2	1.2
Pitch (deg)	Max.	4.7	4.5	4.5	4.5	4.5	3.9	6.3	0.9	4.5
	Min.	-5.1	-4.5	-4.4	-4.0	-4.0	-4.0	-5.4	-0.9	-4.3
	Mean	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Stnd. Dev	1.3	1.2	1.3	1.2	1.2	1.0	1.6	0.2	1.2
Heave (ft)	Max.	37.5	37.5	34.7	31.8	31.0	33.1	46.7	7.4	
	Min.	-36.3	-31.8	-32.8	-33.3	-33.0	-29.8	-45.6	-7.2	
	Mean	1.4	0.9	0.1	0.0	0.0	2.3	0.9	0.0	
	Stnd. Dev	9.9	9.6	10.3	9.7	9.4	7.9	12.9	1.7	

Table 4: Comparison of FPSO Responses in Different WWC Environments to Response in Parallel WWC Conditions

Response	100-Year			Maximum Roll
	Parallel WWC	Non-Parallel WWC	Directional Waves	
Surge			-	-
Line Tension		+		
Heave				
Pitch				
Sway		+	+	+
Roll		+	+	+
Yaw		+	+	+

	Response = Response in Parallel WWC
-	Response < Response in Parallel WWC
+	Response > Response in Parallel WWC

Figure 1: OTRC Wave Basin Layout

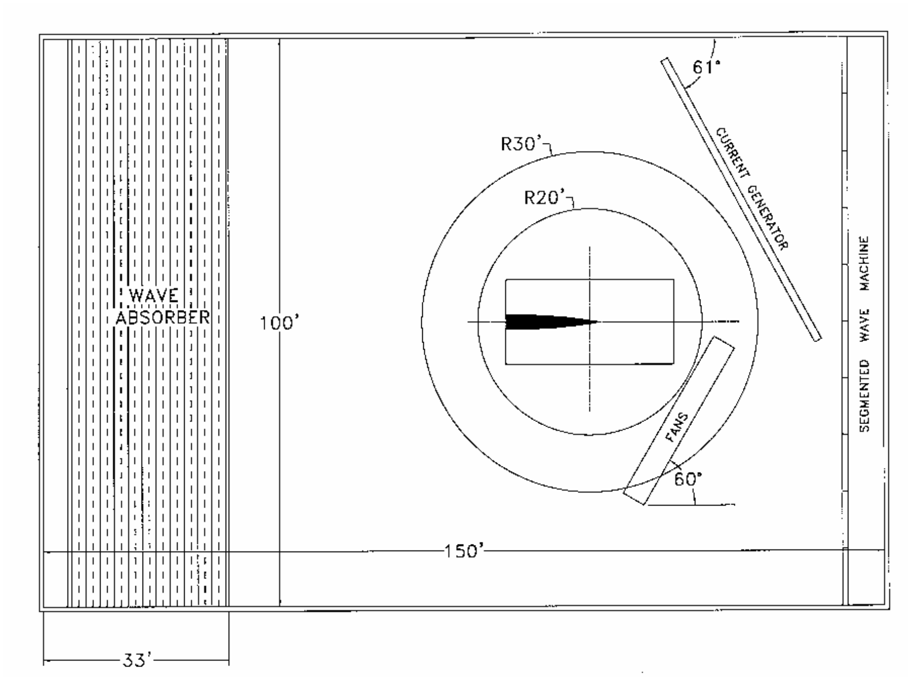

Figure 2: OTRC Wave Basin Con Figure**d for Non- Collinear Wave, Wind, and Current Tests**

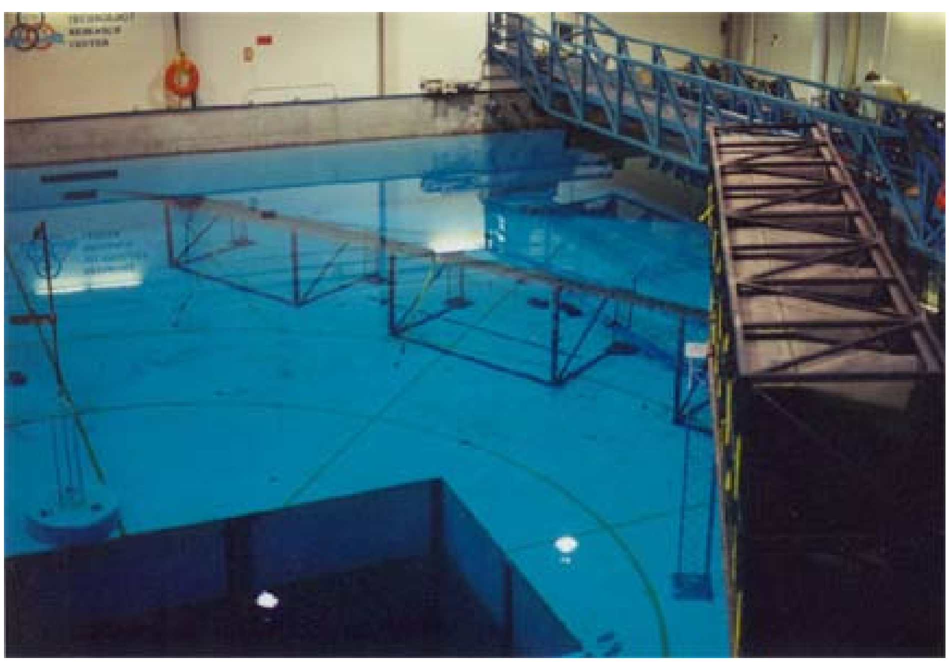

Figure 3: Wave, Wind, & Current Directions at Different Locations in a Hurricane

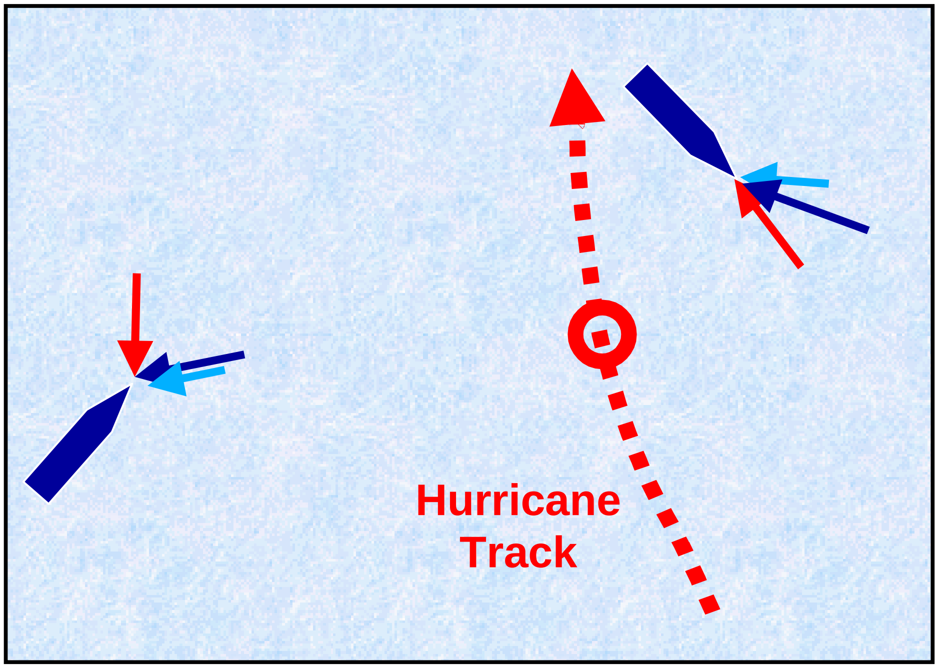

Figure 4: Wind, Wave, Wind, & Current Direction in Different Test Environments

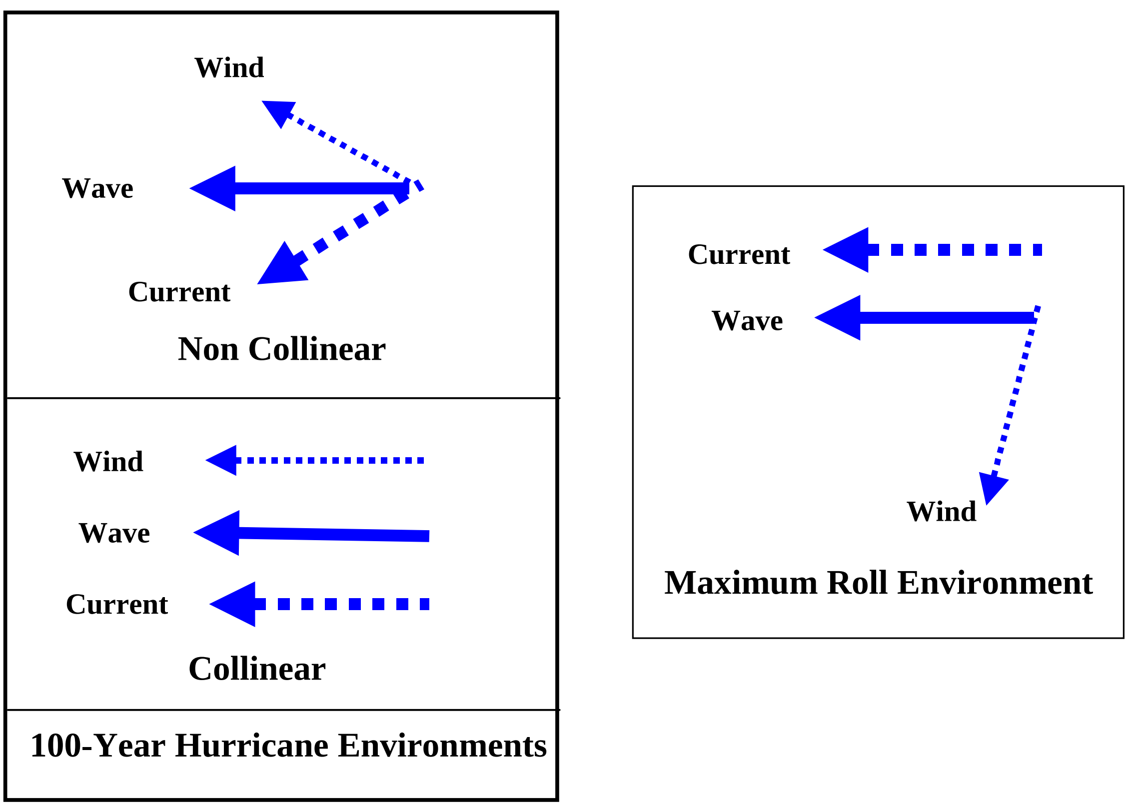

Figure **5: FPSO Model**

Figure**6: FPSO Turret**

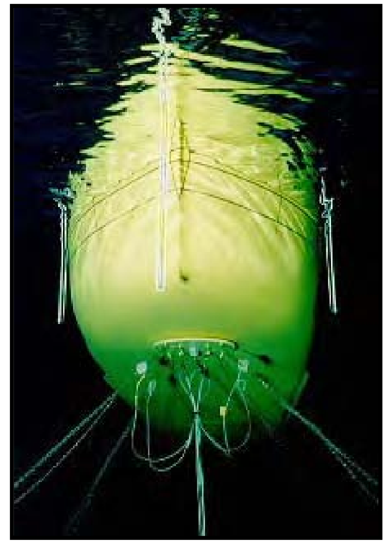

Figure 7: FPSO Model in Wave Basin

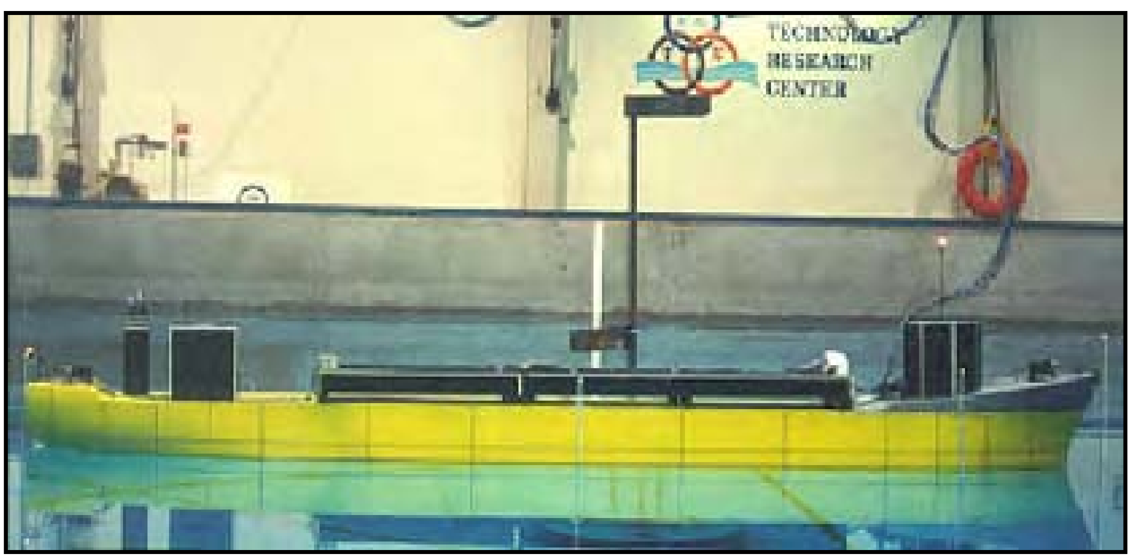

Figure 8: FPSO Model in Parallel Waves, Winds, & Currents

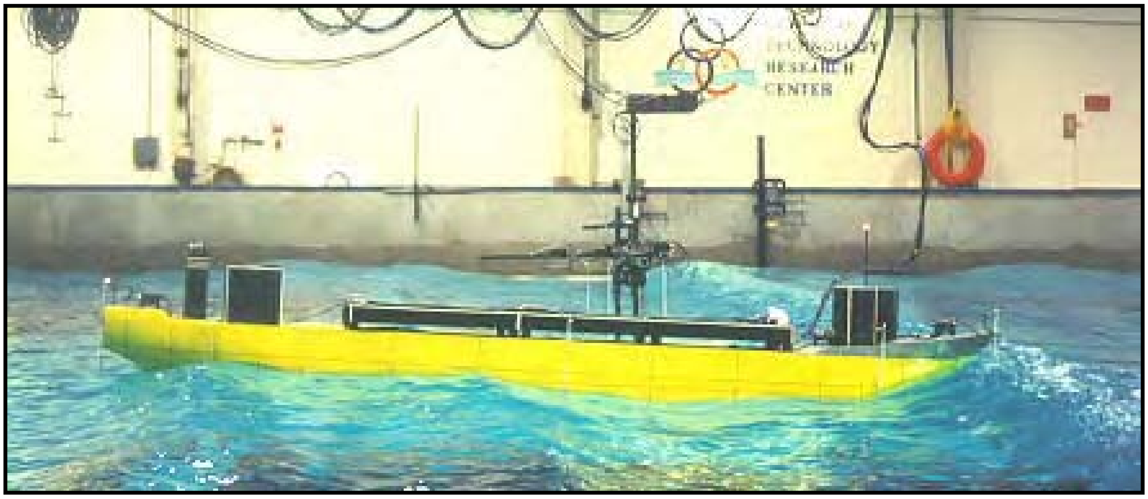

Figure 8: FPSO Model in Non Parallel Waves, Winds, & Currents

Figure 10: FPSO Mooring Line Layouts

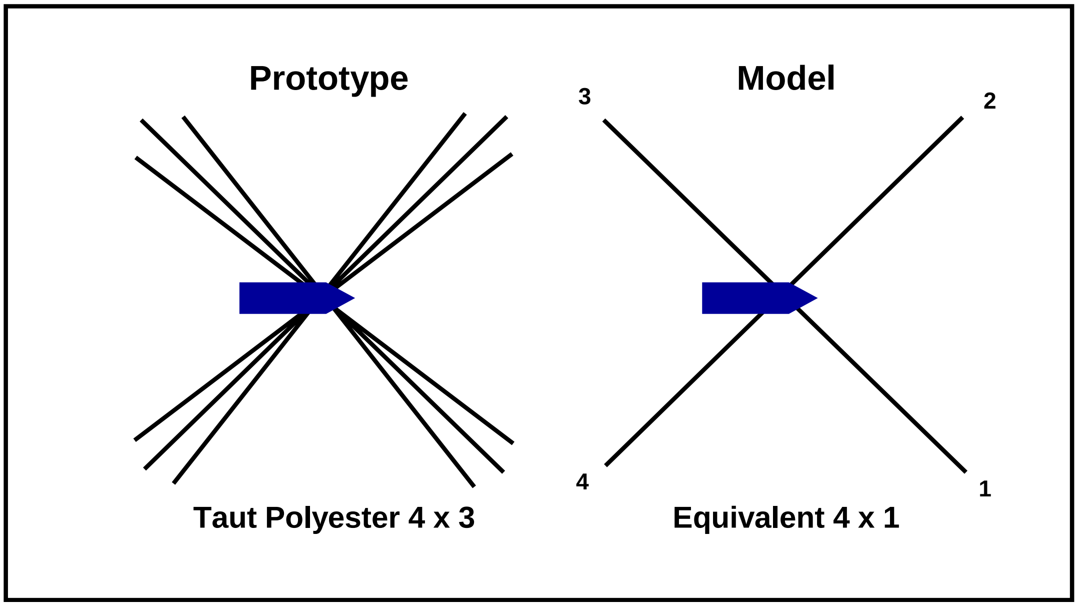

Figure 11: Comparison of Prototype vs. Modeled Truncated Mooring System Force Displacement Characteristics

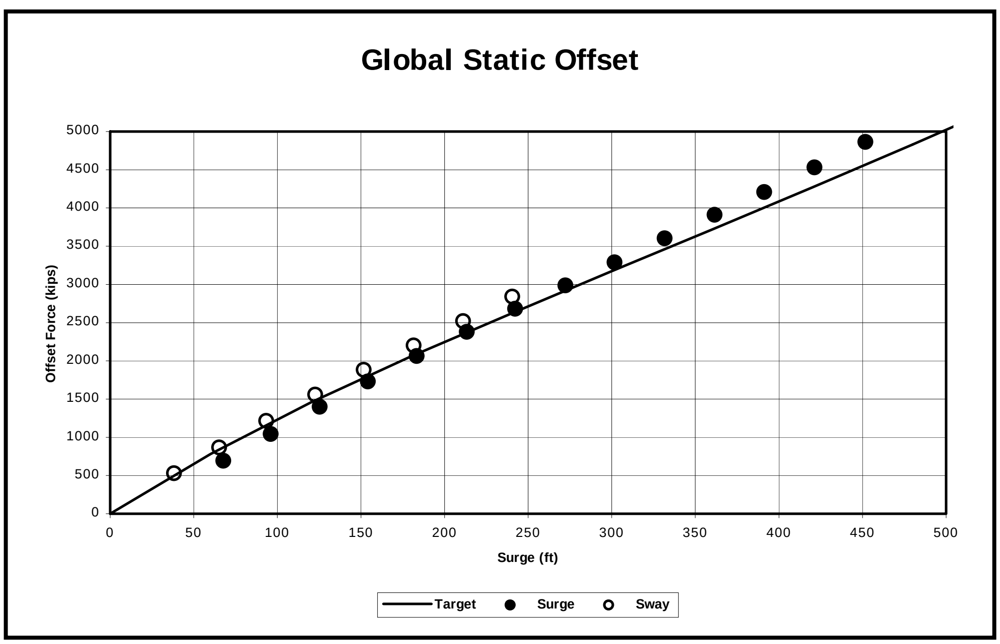

Figure 12: Surge Statistics

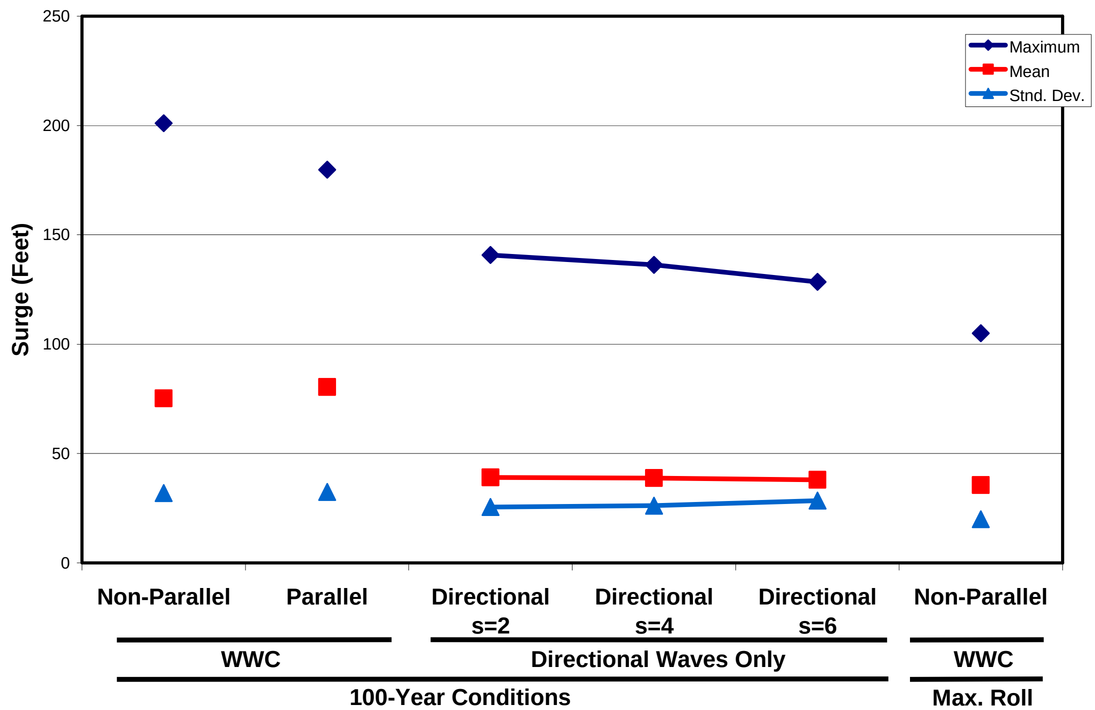

Figure 13: Sway Statistics

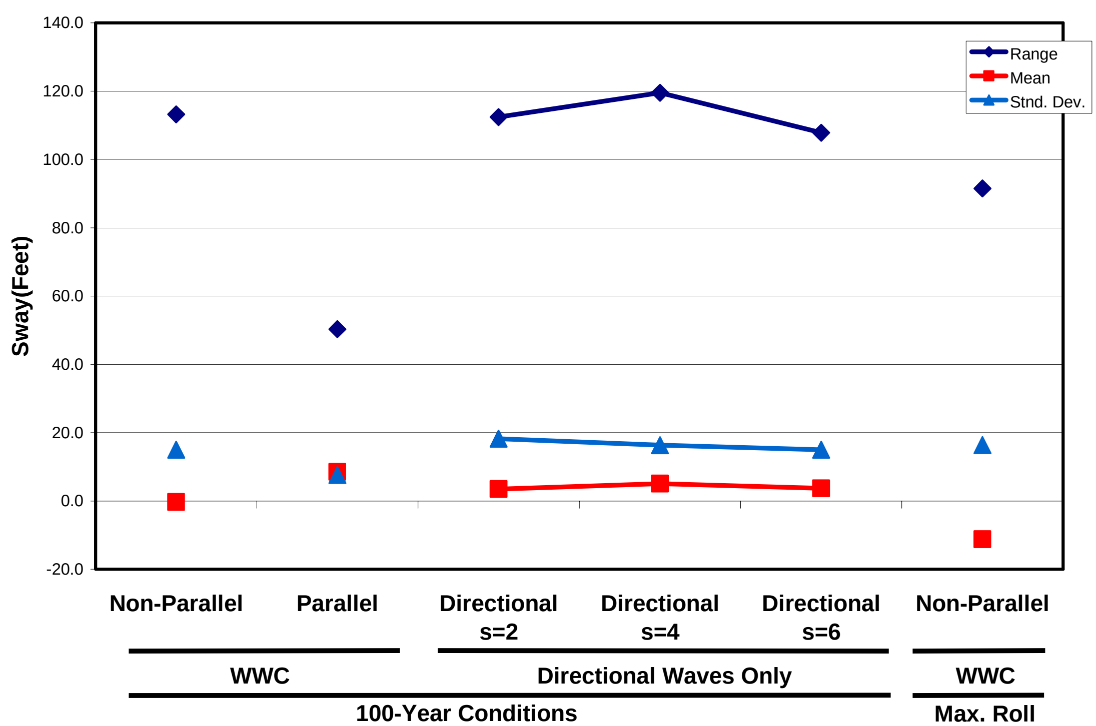

Figure 14: Mooring Line Tensions Statistics

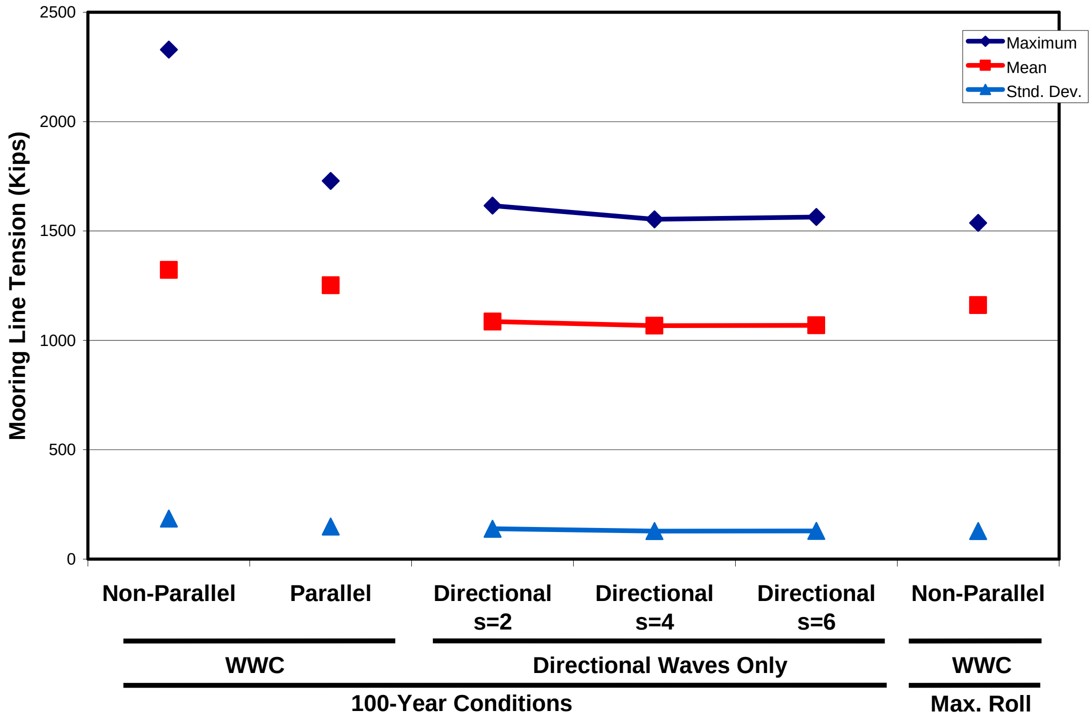

Figure 15: Yaw Statistics

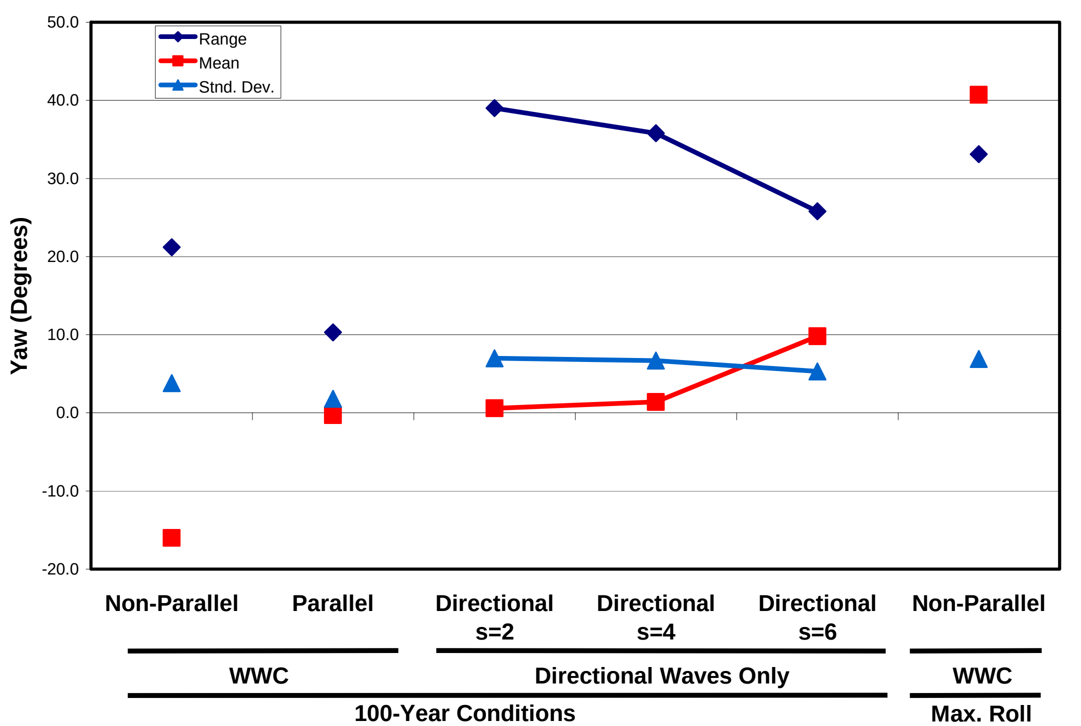

Figure 16: Roll Statistics

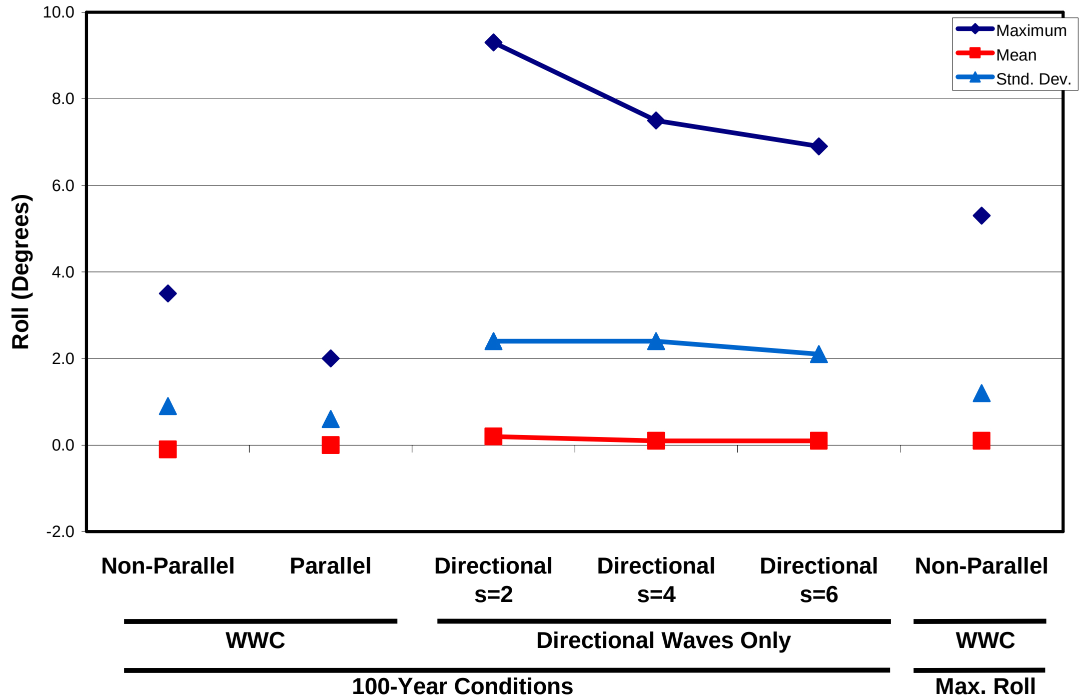

Figure 17: FPSO Surge Spectrum

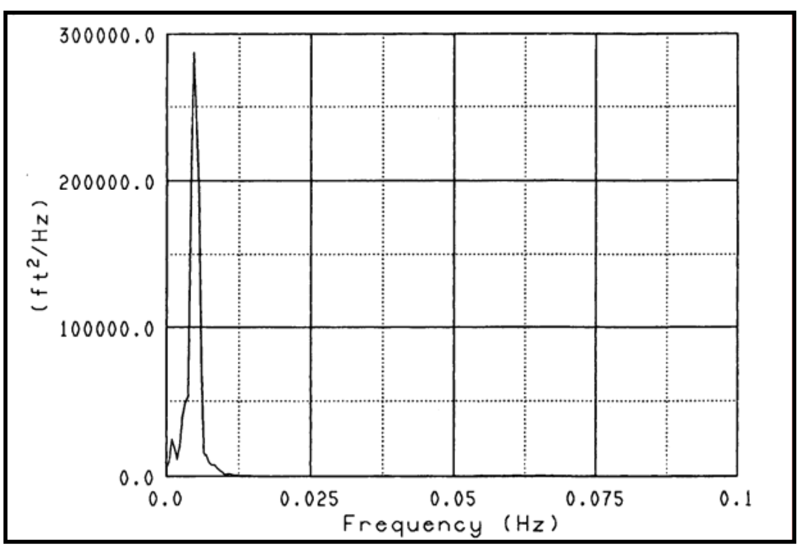

Figure 18: FPSO Mooring Line Spectrum

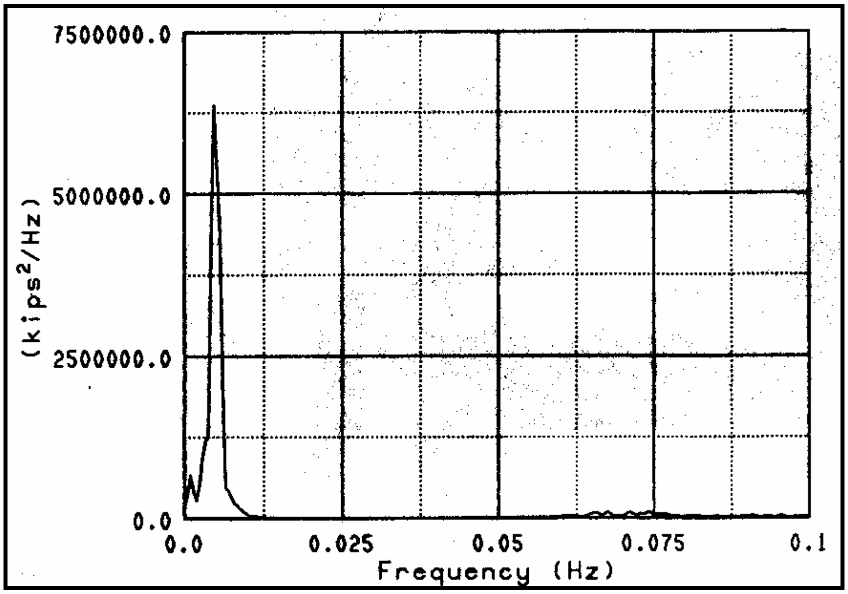

Figure 19: Wave – Yaw Coherence

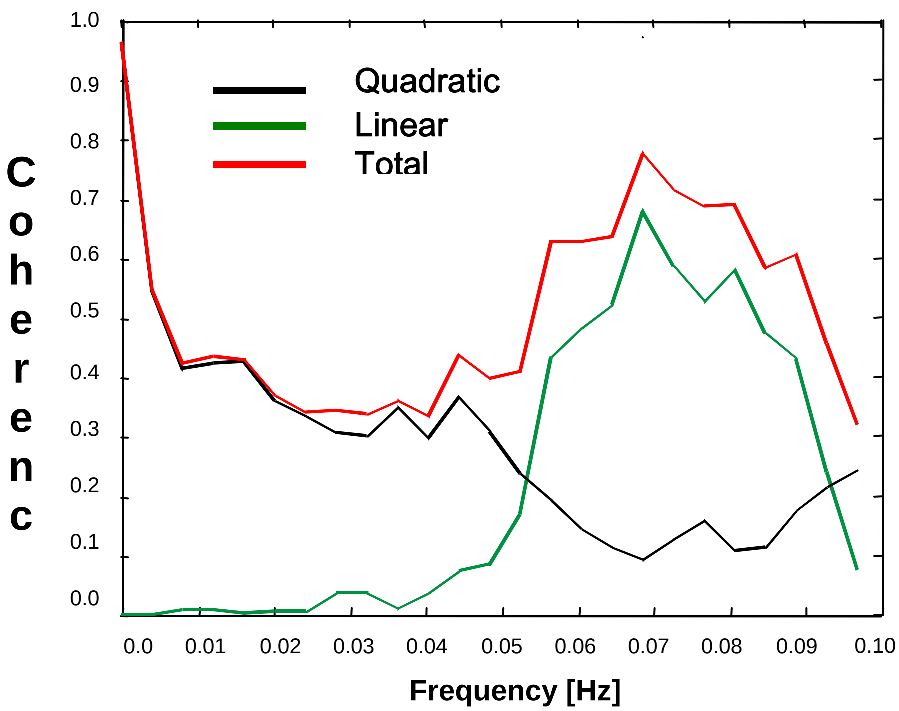

Figure 20: Wind - Yaw Coherence