11th International Symposium on Offshore and Polar Engineering ISOPE
STAVANGER, Norway June 17-22, 2001

Effect of Coupling of Mooring Lines and Risers on the Design Values for a Turret Moored FPSO in Deep Water of the Gulf of Mexico

J.E.W. Wichers
MARIN USA Inc., Houston

P.V. Devlin
Texaco Inc., Bellaire Houston

58

ABSTRACT

In the framework of the DeepStar CTR 4401A "Theme structures" coupled computations were carried out on a turret moored tanker based FPSO in 3,000 ft, 6000 ft and 10, 000 ft water depth for the Gulf of Mexico. The FPSO was exposed to both Hurricane and Loop-current conditions. The size of the FPSO corresponds to a 200 kDWT tanker moored by means of 12 lines. For the production, water injection, oil and gas transport, the turret was provided of a 13 SCR system. The mooring system in 3,000 ft exists of a chain-jacketed spiral strand-ground chain, while the mooring system in 6000 ft was both chain-polyester-ground chain and chain-spring buoys-jacketed spiral strand-ground chain and for 10,000 ft water depth it consists of a chain-polyester-ground chain combined line.

Considering the design values the question may arise on the value of the coupled analysis and the effects of the Cd-values on the dynamics on the mooring legs and risers at large water depth. To understand the questions a fully coupled mathematical model was developed.

Using the DeepStar FPSO system a new set of computations in the time-domain has been carried out. By changing systematically the Cd-resistance coefficients on the risers and the mooring lines the effect of the coupling on the global motions and the mooring forces can be distinguished. The computations were applied for the system in 3,000 ft water depth exposed to the Hurricane and Loop-current condition and in 10,000 ft water depth during Hurricane condition. The results show that the complete coupling has to be taken into account to obtain realistic design values.

KEYWORDS: Coupled, FPSO, mooring forces, riser tension, global motions, deepwater

NOMENCLATURE

C_{dn} : drag coefficient normal
C_{dt} : drag coefficient tangential
C_{in} : added inertia coefficient normal
C_{it} : added inertia coefficient tangential
C_{FN} : coulomb friction seabed normal
C_{FT} : coulomb friction seabed tangential

INTRODUCTION

A turret moored FPSO system generally consists of a tanker (hull, process equipment and a superstructure), a mooring system and a risers system. For the design of the system none of the parts can be neglected. The current loads and the associated damping forces on the mooring lines and the risers will influence not only the watch circle of the turret but also the loads on the risers and the mooring forces. To design a FPSO the complete system has to be taken into account. This is called a fully coupled dynamic system. To formulate coupling effects several studies has been performed in the past (e.g. Wichers and Huijsmans, 1990, van den Boom, 1985, Wichers and Dercksen, 1994).

The forces acting on the system are:

- first order wave forces and hydrodynamic reaction forces with or w/o current on the hull
- second order wave drift forces with or w/o current on the hull
- wave drift damping with or w/o current on the hull
- current loads on the hull
- low frequency hydrodynamic reaction forces on the hull
- first order wave forces, current loads and hydrodynamic reaction forces on the mooring lines and risers
- soil friction reaction forces on the mooring lines and risers.
- aerodynamic exciting and reaction forces; for the excitation e.g. a constant 1-hour mean wind force and wind spectrum forces acting on the above water part of the FPSO.

The sources of these forces will be described in more detail in the associated sections.

In order to demonstrate the coupling effects on the DeepStar system computations have been carried out with a fully coupled dynamic mathematical model. The computations concern the complete FPSO system in 3,000 and 10,000 ft water depth exposed to the Hurricane weather condition and in 3,000 ft exposed to the Loop-current weather condition. For this purpose the resistance coefficient Cd of the risers and the steel spiral strand (3,000 ft) and polyester ropes (10,000 ft) were varied. The variation concerns the Cd=0, Cd=1 and Cd=2 of the mooring lines and risers. Finally, to demonstrate clearly the coupling effects, computations were carried out with the same varied Cd-values in Loop-current only.

The results of the computations are presented and discussed in this paper.

THE SYSTEM AND DEFINITIONS

The DeepStar FPSO system for the 3,000 ft is shown in Fig. 1. For the 3,000 ft the mooring system consists of a 4*3 chain-spiral strand wire-chain leg system.

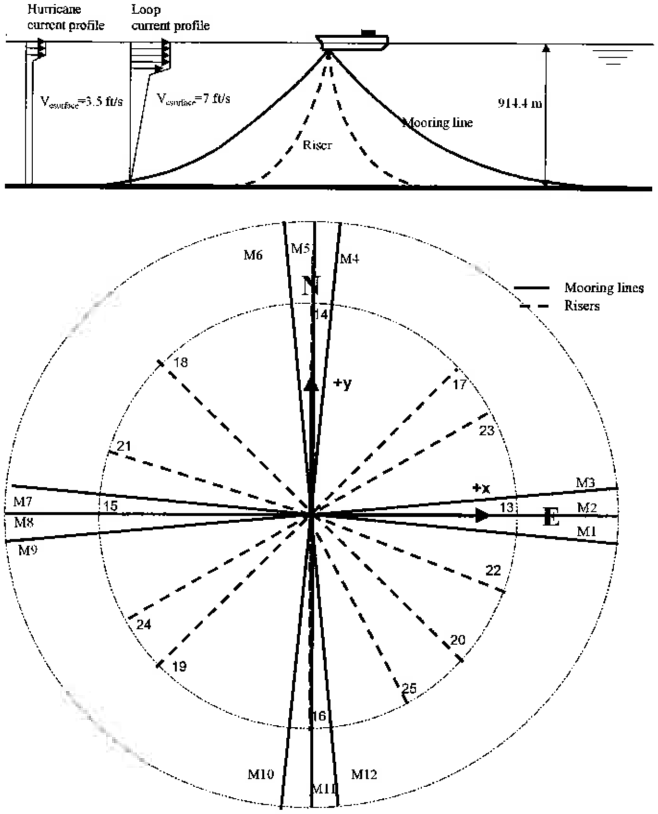

Figure 1. Layout mooring and riser system and system of co-ordinates (3,000 ft water depth).

In 10,000 ft water depth the mooring lines consist of a 4*3 taught chain-polyester rope-chain leg system, while the riser layout and properties of the risers (except for the length and top tension) were kept the same.

The weather conditions, tanker motions, the orientation of the mooring and riser system are defined in an earth-bound system of co-ordinates, see Fig. 1. The yaw displacements of the tanker, the orientation of the mooring lines and risers and the directions of the wave, wind and current are defined anti-clockwise with regard to the positive x-axis (East).

PARTICULARS OF THE SYSTEM

The particulars of the tanker based FPSO are given in Table 1. The particulars of the mooring system and the risers for both the 3,000 ft and 10,000 ft water depth are specified in the Tables 2 and 3 respectively. The mooring system consists of 4 groups of 3 legs. The 3,000 ft mooring leg consists of a chain-spiral strand steel wire-chain system and the 10,000 ft mooring leg is a chain-long polyester rope-chain system.

The riser system exists of:

- 4 liquid production risers
- 4 gas production risers
- 2 water injection risers
- 2 gas injection risers
- 1 gas export riser

The relative long jacketed spiral strand steel wire has a diameter of 3.5", while the diameter of very long polyester rope is 7.09". The diameters of the liquid production, gas production, water injection, gas injection and gas export risers are 17.5", 15.2", 14.8", 8" and 13.5" respectively. In terms of current loads it may be expected that the risers system will take the dominant loads.

Table 1
Particulars of the FPSO tanker

Designation	*Symbol*	*Unit*	*Quantity*
Production level		bpd	120,000
Storage		bbls	1,440,000
Vessel size		kDWT	200
Length between perpendiculars	Lpp	m	310
Breadth	B	m	47.17
Depth	H	m	28.04
Draft	T	m	18.9
Displacement	D	mt	240,869
Center of buoyancy forward of section 10	FB	m	6.6
Center of gravity above base	KG	m	13.32
Metacentric height transverse	GMt	m	5.78
Metacentric height longitudinal	GMl	m	403.83
Transverse radius of gyration in air	Kxx	m	14.77
Longitudinal radius of gyration in air	Kyy	m	77.47
Yaw radius of gyration in air	Kzz	m	79.3
Roll period in water	Tf	s	13.9
Wind area frontal	Af	m^2	1,012
Wind area side	As	m^2	3,772
Turret in centerline behind Fpp (20.5% Lpp)	-	m	63.55
Turret elevation below tanker base	-	m	1.52
Turret diameter	-	m	15.85
Bilge keel length (station 7 to 14) Lbk = 108.5 m; height Hbk = 0.825 m			
Rudder attached; no propeller			

Table 2
Particulars of mooring system

Designation	*Unit*	*Quantity*	
Water depth	m	914	3,048
Pre-tension	kN	1,201	1,691
Number of lines		4*3	
Degrees between the 3 lines	deg	5	
Length of mooring line	m	2,088	4,267.2
Radius of chain stoppers turntable	m	7	
Segment 1 (ground section): Chain		K4 studless	
Length at anchor point	m	914.4	121.9
Diameter	mm	88.9	101.6
Dry weight	N/m	1,617.10	2,112.5
Weight in water	N/m	1,406.90	1,837.5
Stiffness AE	kN	794,484	1,037,720
Mean breaking load (MBL)	kN	6,512	8,669
Segment 2: wire		Spiral strand	Polyester
Length	m	1,127.80	4,053.8
Diameter	mm	88.9	180.1
Dry weight	N/m	412.23	213
Weight in water	N/m	349.75	55.6
Stiffness AE	kN	689,858	240,192
Mean breaking load (MBL)	kN	6,418	9,576.4
Segment 3 (top section): Chain		K4 studless	
Length	m	45.7	91.44
Diameter	mm	88.9	101.6
Dry weight	N/m	1,617.09	2,112.5
Weight in water	N/m	1,406.89	1,837.5
Stiffness AE-average	kN	794,484	1,037,720
Mean breaking load (MBL)	kN	6,512	8,669

Table 3
Particulars of riser system

		OD	3,000 ft	10,000 ft
Type riser	Numbering, see Fig. 1	mm	Top-tension in kN	
Liquid production	#13, #14, #15, #16	445	1,112	3,714
Gas production	#17, #18, #19, #20	386	609	2,033
Water injection	#21 (165°), #22 (337.5°)	531	2,019	6,725
Gas injection	#23 (30°), #24 (210°)	287	1,352	4,519
Gas export	#25 (300°)	343	454	1,530

Table 3 (continued)
Particulars of riser system

		EA	Dry weight	UW	EI
Type riser	Numbering, see Fig. 1	kN	N/m	N/m	Nm^2
Liquid production	#13, #14, #15, #16	1.83E+07	1,927	1,036	276
Gas production	#17, #18, #19, #20	1.08E+07	1,708	526	113
Water injection	#21 (165°), #22 (337.5°)	1.86E+07	2,803	1,898	224
Gas injection	#23 (30°), #24 (210°)	3.14E+06	1,810	1,168	64
Gas export	#25 (300°)	8.63E+06	1,358	423	71

STATIC LOADS DISPLACEMENT CURVES

The static load-displacement curves for the system in both 3,000 and 10,000 ft water depth are presented in the Figs. 2 and 3. The static load-displacement curves concern pulling the tanker in the West direction, see Fig. 1.

It must be noted that for the 3,000 ft water depth the static load tends to be stiffer at increasing displacement, while for the 10,000 ft the static load seems to become softer.

The initial stiffness of the 3,000 ft is approximately 70 kN/m, while the initial stiffness in 10,000 ft is approximately 150 kN/m. In spite of the large water depth the taught polyester system is more than 2 times stiffer than the semi-taught spiral strand steel wire system in 3,000 ft. Further Figs. 2 and 3 show that the effect of the riser system on the total restoring force can not be neglected. The contribution of the riser system in 3,000 ft water depth amounts to approximately 20%, while in 10,000 ft the contribution is 10%.

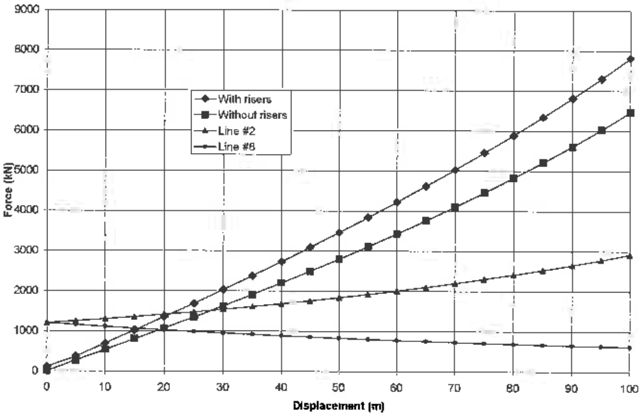

Figure 2. Static load displacement curve for 3,000 ft water depth.

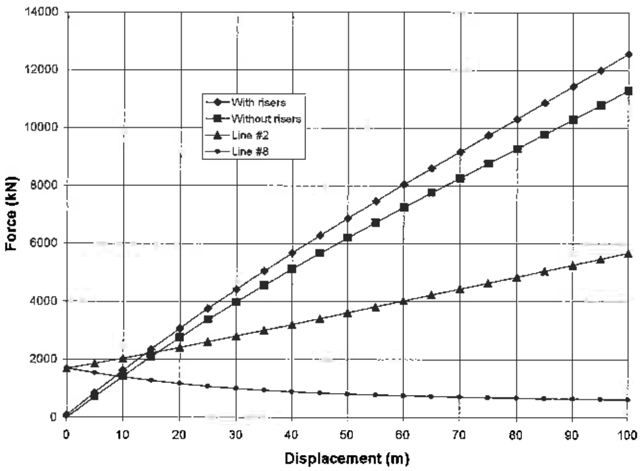

Figure 3. Static load displacement curve for 10,000 ft water depth.

THE WEATHER CONDITIONS

General

The weather conditions as applied to the computations are defined in Table 4. The current profile for the 3,000 ft is presented in Fig. 4. For the computations in 10,000 ft water depth the hurricane profile below 3,000 ft was extended to 10,000 ft.

Table 4
Weather conditions

Description	*Unit*	*Hurricane*	*Loop-current*
Waves:			
Hs	m	12.19	6.1
Tp	s	14	11
Wave spectrum type	-	JONSWAP (γ=2.5)	JONSWAP (γ=2.0)
Wave direction	deg	180	90
Wind:			
1 hour mean speed	m/s	41.12 @ 10 m	22.35 @ 10 m
Wind spectrum type	-	API	API
Direction	deg	210	90
Current:			
Profile		See Fig. 4	See Fig. 4
Direction	deg	150	0

Waves

To define the wave parameters JONSWAP spectra were used for both Hurricane and Loop-current condition.

The theoretical wave spectrum can be determined by

$$S(\omega) = \alpha \cdot g^2 \cdot \omega^{-5} \cdot \exp\left[-\frac{5}{4}\left(\frac{\omega}{\omega_p}\right)^{-4}\right] \cdot \gamma \cdot \exp\left[-\frac{(\omega-\omega_p)^2}{2\sigma^2\omega_p^2}\right] \qquad (1)$$

in which:

α = Phillips constant
g = gravity constant
γ = peakness parameter
σ = 0.07 for $\omega \leq \omega_p$
= 0.09 for $\omega > \omega_p$.

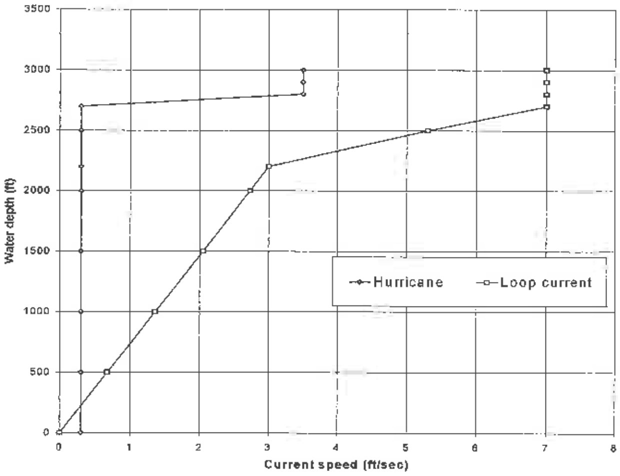

Figure 4. Current profile 3,000 ft water depth.

The Phillips constant can be determined according to the following relation:

$$H_s = 4\sqrt{(m_0)} \qquad (2)$$

and

$$H_s^2 = 16\int_0^\infty S(\omega)\ d\omega \qquad (3)$$

The spectrum of the wave groups can be described as follows:

$$S_{A^2}(\mu) = 8\int_0^\infty S(\omega)\ S(\omega+\mu)\ d\omega \qquad (4)$$

in which:

$S_g(\mu)$ = wave group spectrum
$S_\zeta(\omega)$ = wave spectrum
ω = wave frequency
μ = low frequency.

Wind

The lateral and front wind areas of the FPSO are given in Table 1. For the wind coefficients reference is made to OCIMF data (1994). Based on the one-hour wind speed the API wind spectrum was applied. The description of the API wind spectrum is given below (API-RP2A, 1990):

$$S_{V_w}(\omega) = \frac{\sigma_{V_w}^2(z)}{2\pi\ \ fp\ \left[1+\frac{1.5\ \omega}{2\pi\ fp}\right]^{5/3}} \qquad (5)$$

in which:

ω = frequency in rad/s of wind oscillation
S_{Vw} = spectral density of wind speed in m^2/s
fp = average factor derived from measured wind spectra
= $0.0025\ V_w(z)$

$\sigma_{V_w}(z)$ = turbulence intensity

$$= 0.15 \left(\frac{z}{20}\right)^{\alpha} V_w(z)$$

where:

α = -0.125 for $z \leq 20$ m

α = -0.275 for $z > 20$ m

$V_w(z)$ = the hourly mean wind speed (m/s) at a level z above the water surface.

COMPUTATIONAL APPROACH

Methodology

For the computations the fully coupled dynamic computer program DYNFLOAT-version v_2000 was used. The program has been validated with numerous model tests.

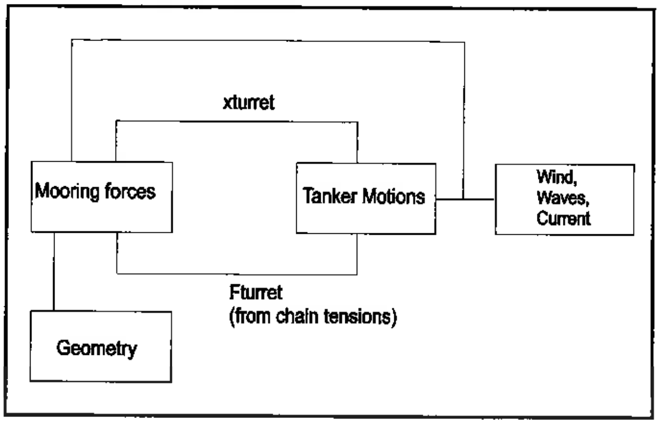

Figure 5. Computational scheme.

For the computational scheme the following method is followed:

- The tanker hydro and aerodynamic tanker loading consists of current loads, wind loads, first order and the second order wave drift forces and the associated damping.
- The turret displacement, velocities and accelerations, the current loads and the associated damping forces affect the motions and forces on the mooring lines.
- The turret displacement, velocities and accelerations, the current loads and the associated damping forces affect the motions and forces on the risers.
- The forces on the mooring lines and risers accumulated in the turret will affect the low frequency motions of the tanker.

Due to the strong non-linear terms in the equations of motion the computations are carried out in the time-domain. At time step t, the equations of motion of the tanker are solved, resulting in the known displacement, velocities and accelerations of the turret (chain, riser attachment points). Next by means of the dynamic mooring line and riser program DYNFLX the full dynamics of each line and riser is computed. After finalizing the dynamics of all lines, the computed forces of all lines are accumulated in the turret. In the next step the equations of motion with the new input is solved etcetera. The coefficients for the mooring lines and risers are defined in Table 5.

Note that the first order wave forces on the mooring lines and risers were not taken into account. These forces are small compared to the current loads, and therefore are not expected to affect the coupled responses.

For the wind and current coefficients as used for the FPSO reference is made to (OCIMF, 2nd edition, 1996).

The transfer functions of the first order wave forces, added mass and damping and the quadratic transfer function (QTF) of the wave drift damping and the wave drift force matrix as acting on the hull was computed. Associated viscous roll damping was added.

For the Hurricane condition the mentioned transfer functions were computed including the effect of the parallel component of the current (Vc=0.93 m/s). For the description of the 3-D potential time-domain program reference is made to (Sierevogel, 1998). Due to the relative small heading with regard to the incident Hurricane waves, the computed wave interval amounts to 5°, while 60 frequencies were used (0.025 with steps of 0.025 up to 1.5 rad/s).

For the Loop-current condition the waves and current are directed perpendicular. This means that no wave-current interaction occurs. The mentioned transfer functions were computed by means of 3-D linear potential theory (Pinkster, 1980). The wave drift damping QTF was taken according to (Aranha, 1994). Due to the relative large heading of the tanker with regard to the incident waves the wave interval amounts to 15°, while 30 frequencies were used (0.05 with steps of 0.05 up to 1.5 rad/s). In both cases the intervals were computed around the mean position of the moored tanker in wind, waves and current.

Knowing the transfer functions and the wave train registration at the mean position of the tanker, the time traces for the first order motions and the registrations of the wave drift forces were computed prior to the simulations. Interpolation was applied during the simulation.

For the low frequency viscous hydrodynamic reaction forces as acting on the hull -the counter part of the wave drift forces- reference is made to (Wichers, 1988).

Sensitivity Study

The computations have been applied to the FPSO in 3,000 ft water depth for both the Hurricane and Loop-current condition and in 10,000 ft water depth for the Hurricane condition. To show the effect on the fully coupled responses, the Cd-values were systematically varied. Three cases can be distinguished being Case I, II and III for Cd=0 (all coefficients zero which means static load displacement curve only=uncoupled), Cd=1 and Cd=2 respectively for both the spiral strand steel and polyester mooring lines and risers. A review of the coefficients is given in Table 5. The inertia coefficients concern the added mass coefficients, while the friction coefficients concerns the friction over the seabed.

Table 5
Varied coefficients

	Case								
	I	II	III	I	II	III	I	II	III
	K4 studless chain			*Steel wire/Polyester*			*Riser*		
C_{dn}	0	2	2	0	1	2	0	1	2
C_{dt}	0	0.65	0.65	0	0.3	0.3	0	0.4	0.4
C_{in}	0	2	2	0	1.15	1.15	0	1	1
C_{it}	0	0.5	0.5	0	0.2	0.2	0	0	0
C_{FN}	0	1	1	0	0.6	0.6	0	0.6	0.6
C_{FT}	0	1	1	0	0.6	0.6	0	0.6	0.6

A clear coupling of the system can be demonstrated if the FPSO system is exposed to the Loop-current only. This only-current case is shown.

All computations for the Hurricane condition were performed in the same wave train with a duration of 3 hours full scale. The same was applied for the Loop-current condition. The mean and the standard deviation will give a good impression of the sensitivity of the Cd-values on the results. For a correct statistical interpretation of the maximum values multiple runs of 3 hours should be carried out.

PRESENTATION OF THE RESULTS

Hurricane Condition in 3,000 ft and 10, 000 ft Water Depth

The results of the computations in Hurricane condition are shown in the Tables 6 and 7. Note that the turret forces are ship-bound. The results of the uncoupled system (Case I - only static load curves of the mooring lines and risers) and the coupled systems (Cases II and III) clearly indicate the need for a coupled system. The uncoupled system gives unrealistic values for tanker motions, mooring forces and riser tensions.

At increasing Cd-values (Cases II and III-100% increase) the results show that the tanker motions slightly decrease and the mooring forces slightly increase or both stay on the same level. The combination of decreased tanker motion due to increased damping on the risers and lines and increased current loads on the risers and lines may result in slightly different or the same motions and mooring loads. The riser tensions, however, increase significantly (especially for the 3,000 ft).

Due to the approximately 2 times stiffer system for 10,000 ft the motions of the tanker are approximately 2 times smaller. In 10,000 ft water depth the dynamic factor in line #2 for Cases II and III defined as Fd = ((max-mean)/standard deviation) amounts to 4.4 and 4.6 respectively. For the 3,000 ft water depth the corresponding dynamic factors are 4.8 and 5.1. The dynamics in the spiral strand steel wire system is slightly higher. Except for the riser tension it can be concluded that doubling of the Cd values will result in the slightly different results (<10%) in 3,000 ft and the same level for 10,000 ft. The sensitivity of Cd on the riser tension, how ever, is significant. The riser forces may increase by 50% in 3,000 ft and by 22% in 10,000 ft.

Loop-Current Condition in 3,000 ft Water Depth

The results of the computations in Loop-current condition in 3,000 ft are presented in Table 8. Note that the turret forces are ship-bound.

As was found in Hurricane condition the results of the uncoupled system (Case I) and the coupled systems (Cases II and III) clearly indicate the need for a coupled system.

Due to possible VIV-motions of the risers (and mooring lines) the Cd-value may increase. At increasing Cd-values (Cases II and III) the dynamic tanker motions in the horizontal plane significantly decrease but the maximum displacements increase significantly. Due to the increased current load on the risers the damping increase resulting in lower dynamic tanker motions but the mean displacement of the tanker increases too, resulting in a higher maximum displacement and associated mooring forces. It can be concluded that the sensitivity of Cd on the tanker motions and mooring forces are significant.

As was found for Hurricane at increasing Cd-value the riser tensions increase significantly also.

Table 6
Results of computations Hurricane condition
3,000 ft water depth

Hurricane 3,000 ft	Unit	Pre-tension	Case I: Cd=0		
			mean	st. dev.	max
Vessel motions:					
x-motion turret	m		-38.1	39.4	-157.1
y-motion turret	m		16.6	20.4	64
Yaw	deg		9.9	7.1	33.8
Force in line #2	kN	1,201	1798	736	9599
Force in line #8	kN	1,201	959	258	2184
X-force turret	kN		2471	3351	23729
Y-force turret	kN		-1401	1617	-16338
Liquid production riser #13	kN	1,112	1176	66	1457
Gas production riser #20	kN	609	652	27	799
Water injection riser #22	kN	2,019	2137	97	2609
Gas injection riser #23	kN	1,352	1420	101	1759
Gas export riser #25	kN	454	474	12	544

Hurricane 3,000 ft	Unit	Pre-tension	Case II: Cd=1		
			mean	st. dev.	max
Vessel motions:					
x-motion turret	m		-42.1	16.2	-96.4
y-motion turret	m		16.6	4.1	30.5
Yaw	deg		12	2.6	21.2
Force in line #2	kN	1,201	1743	351	3433
Force in line #8	kN	1,201	876	201	1985
X-force turret	kN		2480	1363	9065
Y-force turret	kN		-1673	693	-6017
Liquid production riser #13	kN	1,112	1182	292	3921
Gas production riser #20	kN	609	669	268	3451
Water injection riser #22	kN	2,019	2149	363	5481
Gas injection riser #23	kN	1,352	1421	225	3360
Gas export riser #25	kN	454	484	202	2514

Hurricane 3,000 ft	Unit	Pre-tension	Case III: Cd=2		
			mean	st. dev.	max
Vessel motions:					
x-motion turret	m		-42.7	14.1	-88.5
y-motion turret	m		16.9	3.5	28.6
Yaw	deg		12	2.5	20.3
Force in line #2	kN	1,201	1750	337	3458
Force in line #8	kN	1,201	867	215	1997
X-force turret	kN		2478	1299	10493
Y-force turret	kN		-1673	693	-6298
Liquid production riser #13	kN	1,112	1193	414	5313
Gas production riser #20	kN	609	696	402	5135
Water injection riser #22	kN	2,019	2159	516	7099
Gas injection riser #23	kN	1,352	1426	328	4351
Gas export riser #25	kN	454	501	279	3485

Table 7
Results of computations Hurricane condition
10,000 ft water depth

Hurricane 10,000 ft	Unit	Pre-tension	Case I: Cd=0		
			mean	st. dev.	max
Vessel motions:					
x1-motion turret	m		-18.7	19.5	-76.2
x2-motion turret	m		4.7	8.3	27.9
Yaw	deg		10.2	3.3	22.8
Force in line #2	kN	1,691	2569	390	4235
Force in line #8	kN	1,691	1299	428	3029
X-force turret	kN		2445	3056	6870
Y-force turret	kN		-1487	1307	-8034
Liquid production riser #13	kN	3,714	3738	25	3810
Gas production riser #20	kN	2,033	2048	12	2096
Water injection riser #22	kN	6,725	6768	38	6901
Gas injection riser #23	kN	4,519	4547	38	4664
Gas export riser #25	kN	1,530	1538	6	1563

Hurricane 10,000 ft	Unit	Pre-tension	Case II: Cd=1		
			mean	st. dev.	max
Vessel motions:					
x1-motion turret	m		-19.5	8.3	-53.7
x2-motion turret	m		5.5	2	14.4
Yaw	deg		10.7	1.7	16.8
Force in line #2	kN	1,691	2398	328	3836
Force in line #8	kN	1,691	1181	237	2062
X-force turret	kN		2434	2047	12089
Y-force turret	kN		-1510	669	-6290
Liquid production riser #13	kN	3,714	3757	825	11384
Gas production riser #20	kN	2,033	2079	797	9013
Water injection riser #22	kN	6,725	6789	1009	15752
Gas injection riser #23	kN	4,519	4551	689	9126
Gas export riser #25	kN	1,530	1560	610	7046

Hurricane 10,000 ft	Unit	Pre-tension	Case III: Cd=2		
			mean	st. dev.	max
Vessel motions:					
x1-motion turret	m		-20.4	7.8	-53.8
x2-motion turret	m		6	1.7	14.2
Yaw	deg		10.7	1.7	16.3
Force in line #2	kN	1,691	2436	310	3853
Force in line #8	kN	1,691	1151	231	2028
X-force turret	kN		2435	2093	12092
Y-force turret	kN		-1508	659	-6190
Liquid production riser #13	kN	3,714	3783	1082	13484
Gas production riser #20	kN	2,033	2128	1045	11009
Water injection riser #22	kN	6,725	6821	1292	17863
Gas injection riser #23	kN	4,519	4562	786	9608
Gas export riser #25	kN	1,530	1591	775	8346

Table 8
Results of computations in Loop-current condition
3, 000 ft water depth

Loop-current 3,000 ft	Unit	Pre-tension	Case I: Cd=0		
			mean	st. dev.	max
Vessel motions:					
x-motion turret	m		26.7	7.7	49.3
y-motion turret	m		-15.4	12.8	-54.2
Yaw	deg		227	4.2	242
Force in line #8	kN	1,201	1505	101	1848
Force in line #2	kN	1,201	979	56	1161
X-force turret	kN		568	476	3055
Y-force turret	kN		-1881	936	-4969
Liquid production riser #15	kN	1,112	1151	12	1192
Gas production riser #19	kN	609	618	7	650
Water injection riser #21	kN	2,019	2096	27	2194
Gas injection riser #24	kN	1,352	1387	13	1429
Gas export riser #25	kN	454	441	7	469

Loop-current 3,000 ft	Unit	Pre-tension	Case II: Cd=1		
			mean	st. dev.	max
Vessel motions:					
x-motion turret	m		55.7	3.6	66.4
y-motion turret	m		-15.4	8.4	-31.9
Yaw	deg		227	3.3	238
Force in line #8	kN	1,201	1943	119	2338
Force in line #2	kN	1,201	785	50	1092
X-force turret	kN		572	412	2776
Y-force turret	kN		-1876	758	-3969
Liquid production riser #15	kN	1,112	1230	74	1777
Gas production riser #19	kN	609	665	64	1226
Water injection riser #21	kN	2,019	2212	88	2825
Gas injection riser #24	kN	1,352	1468	66	1924
Gas export riser #25	kN	454	432	46	786

Loop-current 3,000 ft	Unit	Pre-tension	Case III: Cd=2		
			mean	st. dev.	max
Vessel motions:					
x-motion turret	m		77	2.8	85.5
y-motion turret	m		-15.1	7.1	-29.4
Yaw	deg		227	3.1	236.9
Force in line #8	kN	1,201	2372	142	2833
Force in line #2	kN	1,201	667	53	968
X-force turret	kN		570	418	2800
Y-force turret	kN		-1871	770	-4013
Liquid production riser #15	kN	1,112	1312	122	2263
Gas production riser #19	kN	609	718	108	1613
Water injection riser #21	kN	2,019	2331	142	3408
Gas injection riser #24	kN	1,352	1549	104	2336
Gas export riser #25	kN	454	424	41	749

The Current Loads on the Risers during the Loop-Current

To elucidate the current loads on risers and mooring legs and the effect of the coupling in terms of tanker offset computations were carried out in Loop-current only. The results are shown in Fig. 6.

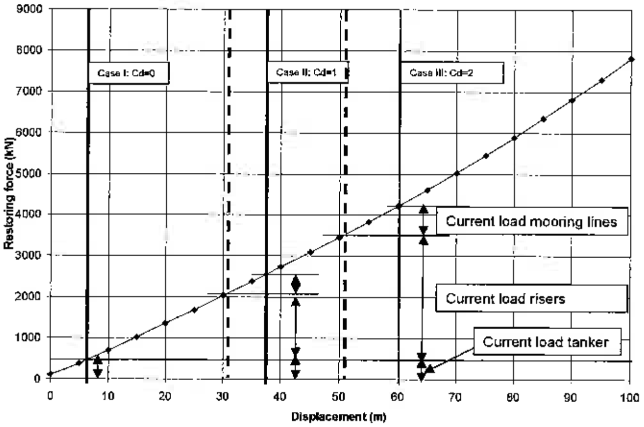

Figure 6. Current loads on the risers in Loop-current (3,000 ft).

The following computations in 3,000 ft exposed to Loop-current only were carried:

- Case I: uncoupled Cd=0 (mean displacement =7.4 m)
- Case II-a: all risers and steel wires Cd=1 (mean displacement = 37.4 m)
- Case II-b: all risers Cd=1, chain-steel wire-chain legs Cd=0 (mean displacement =31.1 m)
- Case III-a: all risers and steel wires Cd=2 (mean displacement = 60.4 m)
- Case III-b: all risers Cd=2, chain-steel wire-chain legs Cd=0 (mean displacement =51.3 m).

From Fig. 6 it can be learned that the horizontal current on the risers amounts to $F_{hr}(Cd=1) = 1620$ kN, while for $F_{hr}(Cd=2) = 3080$ kN. The horizontal forces on the mooring system amounts to $F_{hm}(Cd=1) = 520$ kN, while for $F_{hm}(Cd=2) = 700$ kN. The results clearly indicate the importance of coupled systems. The current loads on both risers and mooring lines dominate the displacement of the tanker. The load on the tanker was 465 kN.

CONCLUSIONS

The following conclusions can be drawn:

1. From the results of the turret moored FPSO system (tanker, mooring system and riser system) exposed to both Hurricane and Loop-current condition in 3,000 ft and for the Hurricane in 10,000 ft, it can be clearly concluded that fully coupled dynamic mathematical models are necessary to estimate realistic design values.
2. Hurricane condition: At increasing Cd-value the dynamic riser tensions increase significantly for both the 3,000 and 10,000 ft water depth. The sensitivity of Cd (=1 or 2) on the mooring forces, however, is relatively small.
3. Loop-current condition: At increasing Cd-value the dynamic riser tensions increase significantly. The values, however, are smaller than for the hurricane condition; in Loop-current the heave of the turret is relatively smaller. The sensitivity of Cd on the displacement of the tanker and mooring forces is significant; this is caused by the fact that in Loop-current the current loads on risers and mooring system dominate the displacement of the tanker.

Note that the DeepStar JIP tested this FPSO at MARIN in 3,000 ft water depth including complete models of the mooring and riser systems. The environmental conditions were identical to those presented in this paper. Model test results cannot be shown here because they are proprietary to the project participants. However, the model tests support the conclusions of this paper, especially when the Cd on the risers was dominated by VIV response.

REFERENCES

API-RP2A 19th edition (1990). "Recommended Practice for Planning, Designing and Construction Fixed Platforms".

Aranha, JAP (1994). "A Formula for Wave Damping in the Drift for a Floating Body," *J Fluid Mechanics*, 275, 147-155.

Boom, HJJ van den (1985). "Dynamic Behaviour of Mooring Lines," *BOSS Conference*, Delft.

DeepStar-CTR 4401A report (2000). "Theme Structures - Benchmark Analysis for Tanker Based FPSO - GoM," February 2000.

OCIMF (Oil Companies International Marine Forum), 2nd Ed. (1996). "Prediction of Wind and Current Loads on VLCCs," London.

Pinkster, JA (1980). "Low Frequency Second Order Wave Exciting Forces on Floating Structures," PhD, Delft University of Technology.

Sierevogel, LM (1998). "Time-Domain Calculations of Ship Motions," PhD, Delft University of Technology.

Wichers, JEW (1988). "A Simulation Model for a Single Point Moored Tanker," PhD, Delft University of Technology.

Wichers, JEW and Huijsmans, RHM (1990). "The Contribution of Hydrodynamic Damping induced by Mooring Chains on Low Frequency Vessel Motions," *OTC*, Paper No 6218.

Wichers, JEW and Dercksen, A (1994). "Investigation into Scale Effects on Motions and Mooring Forces of a Turret-Moored Tanker," *OTC*, Paper No 7444.