Model Test vs. Virtual Simulation of A VLCC Class FPSO Hookup

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Abstract

A VLCC class FPSO is to be hooked up to a rotational Soft Yoke Mooring System (SYMS) at the Penglai 19-3 field located in the Northern Chinese Waters to the Southeast of the Bohai Bay, close to the Bohai Straits, where the water depth is 27.6 meters and the environment is relatively benign and multidirectional. A wave basin test was conducted at the State Key Laboratory of Ocean Engineering (SKLOE) of Shanghai Jiao Tong University (SJTU) whilst a virtual simulation was performed at the Rotterdam STC Simulation Facility, respectively, for the PL19-3 II FPSO Hookup.

This paper will describe the model test and the virtual simulation respectively for the FPSO hookup, as well as address their different applications for the mating operation between the FPSO and the SYMS in shallow water. The scope of the model test and the virtual simulation covers various installation stages including a series of positioning trials, positioning keeping and temporary mooring to the pre-installed SYMS mooring tower, pendulum mating, and yoke ballasting to storm-safe. The model test is to accurately verify bollard pull capacity to keep the FPSO in position and assess motion responses and mooring loads for the FPSO and installation vessels during various installation stages. The virtual simulation is to provide a virtual-reality environment, thus realistically replicating the hookup operation at the STC facility and identifying any deficiencies in key installation personnel, execution plan, or operation procedures. The methodologies of the model test and the virtual simulation addressed here can be easily extended to the deepwater applications such as positioning and installation operations of various floating systems.

Keywords: FPSO, SYMS, Model Test, Virtual Simulation.

Abbreviations

AHTS = Anchor Handling Tow Supply
FPSO = Floating Production Storage Offloading
SJTU = Shanghai Jiao Tong University
STC = Simulation Test Center
SYMS = Soft Yoke Mooring System
VLCC = Very Large Crude Carrier

Introduction

A VLCC class FPSO is scheduled to be installed late 2008 at the Penglai 19-3 field located in the Northern Chinese Waters to the Southeast of the Bohai Bay close to Bohai Straits. The Field Development includes a rotational Soft Yoke Mooring System pre-installed on the top of a jacket substructure and a VLCC class FPSO to be connected with the SYMS via two yokes and pendulums. The water depth is approximately 27.6 meters while the environment is relatively benign and multidirectional. Refer to Fig. 1 for the overview of the general field layout.

The FPSO will be towed from the SMOE Yard in Singapore to the field by two tugs, each having a bollard pull of 157Te or greater. The FPSO will be ballasted to the positioning drafts prior to arrival at the Handover Location and handover to the Installation Team. Upon arrival in the field, three additional tugs will be connected to the FPSO. The five tugs together form the positioning spread, which will keep the vessel steady and within required watch-circle when mating to the SYMS. After an on-site positioning trial is performed, the positioning spread will move the FPSO approaching towards the SYMS. The vessel will be aligned to the yokes, while maintaining heading towards the prevailing weather.

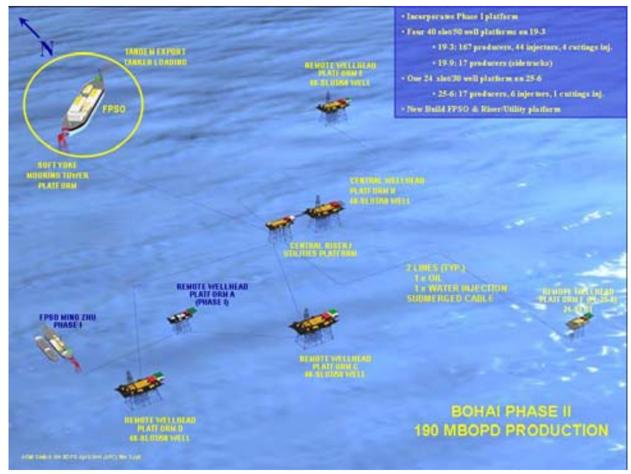

Fig. 1: Overview of General Field Layout

Before the actual mating can commence, the pendulums need to be released from their seafastening clamps. The pendulums are seafastened to inclined braces of the PSS, and have to be swung back to vertical position in a controlled manner. The FPSO will be moored to the turntable on the SYMS tower with 2 substantial Dyneema ropes before any attempt at connecting the Pendulums to the SYMS is made. These ropes will be crossed across the bow of the FPSO to the SYMS. With the help of the mooring lines and the bow tugs, the FPSO will be positioned at its required distance to the SYMS. The positioning spread will continue to keep the vessel steady so that the mating can be done by connecting the yoke arms that extend from the SYMS to the pendulums that are suspended from the PSS at the bow of the FPSO. Temporary buoyancy pontoons are used to support the ends of the yoke arms. The yoke arms are raised from the temporary support through pull-in chains. First these chains are lowered from inside the pendulums and connected to padeyes on the uni-joint forks at the end of the yoke arms. When the chains are jacked in and the arms come loose from the supports, the support frames will automatically be released and slide away to create an air gap. This will avoid clashing between the arms and the support points when heaving.

Once the flanges of the pendulums and the uni-joints come together, guide pins will be installed to assist with alignment. The final connection will be made by bolting the flanges together. Then the ballast tanks of yoke arms will be ballasted with concrete slurry while the anti-yaw tanks will be filled with fresh water. Only after the ballasting is finished, the FPSO is considered storm-safe and can the positioning spread be released. The SYMS freely rotates on the jacket substructure to allow the FPSO to face the prevailing environmental conditions at all times after installation.

The objective of the model test and the virtual simulation outlined herein is to guide the installation design and fine-tune the hookup procedures, thus enabling the FPSO to be hooked up as rapidly as possible, co-incident with safe practice and to enable the subsequent yoke ballasting operations as necessary to provide a storm safe operation, as well as successful post installation of jumpers and cables as smoothly and efficiently as possible.

FPSO & SYMS

The FPSO is permanently moored to the SYMS Mooring Tower. Main functions of SYMS Mooring Tower are described in the following:

- SYMS Mooring Tower allows the FPSO to rotate 360 degrees around the SYMS.
- SYMS Mooring Tower provides for transfer of well fluids, diesel, solids slurry, fiber optic signals, water re-injection fluid, fuel gas, and hydraulic controls between the FPSO and other platforms of the field development during the operating environmental conditions.

The Soft Yoke Mooring System includes the following major components:

- Jacket Substructure
- Topsides Structure
- Mooring Support Structure (MSS) which consists of the Hose Connection Structure and Pendulum Support Structure (PSS).
- Rotating Assembly
- Swivel Stack and Bearings
- Soft Yoke Assembly
- FPSO Mounted Structure
- Jumper Lines including Risers and Cables

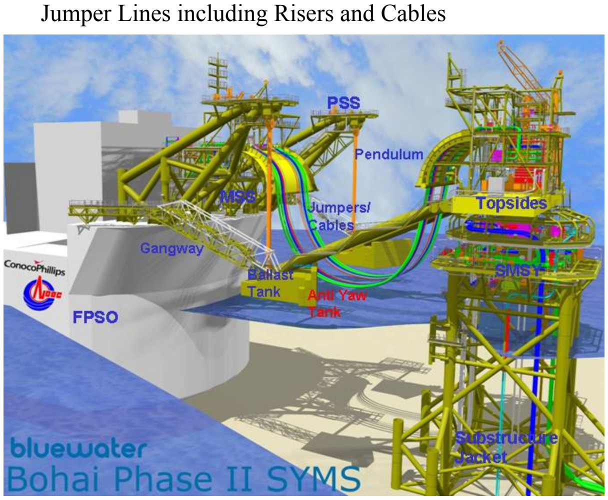

Fig. 2: 3D Illustration of the FPSO and SYMS System

The principal particulars and technical details of the FPSO and the SYMS system are given in the following tables:

Table 1: Principal Particulars of FPSO

Parameters	Value
Water Depth	27.6m
LOA	323.000m
LBP	313.000m
Breadth Moulded	63.000m
Depth Moulded	32.500m
Design Draft Moulded	20.000m
Lightship Weight	113,337Te
Mating Draft even trim & even heel	14.000m
Displacement at mating draft=14m	272,365Te
Water Plane Area	19,232m^2
Frontal Windage	3,179m^2
Side Windage	17,087m^2
LCG from bow	163.100m
TCG from centerline	0.000m
VCG from keel	20.290m
Fairlead Position Forward from Amidships Off the Centerline	 159.800m 15.500m
Pendulum Position Forward from Amidships Off the Centerline	 179.500m 19.000m

Table 2: Principal Particulars of SYMS System

Parameters	Value
SYMS Mooring Tower Design Center:	N 38º23'33.983" E 120º4'52.371" WGS 84, UTM51 (CM123), N 4,253,437.25, E 245,086
Topsides Weight	3,040Te
Moment of Inertia	1.19×10^6Te·m^2
Friction of Turret	880kN·m
Moment Threshold (Breakout)	1,250kN·m
Position of the Mooring Padeyes Center to Design Center Off the Centerline	 7.300m 12.500m
Position of Pendulum Connections Center to Design Center Off the Centerline	 42.000m 19.000m
Topside Dimensions Overall Length Overall Width Overall Height	 41.500m 28.000m 37.000m
Jacket Substructure Weight	1,703Te
Jacket Substructure Dimensions: Overall Length Overall Width Overall Height	 39.000m 39.000m 43.000m
Weight of Yoke Arms	2×410Te
Yoke Arm Dimensions: Overall Length Overall Width Overall Height	 39.500m 30.000m 16.000m
Weight of Temporary Buoyancy Pontoons (TBP)	2×125Te in air
Dimensions of TBPs: Overall Length Overall Width Overall Height	 20.000m 15.000m 5.000m
Volume of Ballast Tanks	2×385m^3 Concrete
Volume of Anti-Yaw Tanks	2×90m^3

	Fresh water
Pendulum Weight	2×103Te
Pendulum Dimension	Ø2.020m×28m high

Fig. 2 illustrates the 3-D configuration of the FPSO and SYMS upon hookup while Fig. 3 shows the elevation view of the FPSO.

Marine Spread for FPSO Positioning

Positional control of the FPSO will be achieved by five AHTS tugs, two of which are the tugs used for the long tow of the FPSO from the SMOE Yard, Singapore to Bohai Bay. The remaining three tugs will mobilize to Bohai Bay and meet the FPSO upon its arrival in the field. Refer to Table 3 for the bollard pull requirements.

Table 3: Marine Spread for FPSO Positioning

AHTS	Location	Bollard Pull
Tug 1	Port Bow	157Te connected to Bracket
Tug 2	STBD Bow	157Te connected to Bracket
Tug 3	STBD Quartering	100Te connected to Bollard
Tug 4	Center Stern	165Te connected to Bracket
Tug 5	Port Quartering	100Te connected to Bollard

The FPSO will be temporarily moored by 2 lines to the SYMS before the pendulums are connected to the yokes. The temporary mooring lines will be made up of Ø80mm×56.3m Dyneema rope shackled to Ø76mm×7m studless chain. The chain will be fitted with a buoy to keep it at surface level. The lines will be connected to padeyes on the SYMS and passed across to the SYMS utilizing the existing mooring lines on the FPSO forward winches. The short length of chain on each mooring will be secured in the fairleads of the FPSO utilizing the existing bollards and a short Dyneema rope strop with a shackle into the studless chain. Both lines will be connected to the SYMS before they are tensioned and locked off on the FPSO using the short length of chain and a length of Ø80mm Dyneema rope secured to bollards.

The 5 positioning lines will comprise of a Ø76mm×12m section of chafe chain connected to the respective tow bracket for Tug 1 & 2 and a Ø76mm×11m chafe chain for Tug 4. Tugs 3 & 5 will be connected to bollards using a Ø80mm Dyneema rope strop. The remainder of the line comprises 50m of nylon spring, i.e. Ø112mm grommet, for 110Te BP Tugs 3 & 5 tug lines, respectively, and Ø136mm grommet for 150 Tugs 1 & 2 and 165Te BP Tug 4 tug lines, respectively, connected by thimble and 120Te shackle to the chafe chain, and by soft eye to soft eye connection to 450m of plasma rope, i.e. Ø60mm rope for 110t BP tug lines and Ø72mm rope for 165Te BP tug lines, respectively. The soft towlines will be fitted with reflective tape at intervals of 15m.

Met-Ocean Data

The requirement for bollard pulls is subject to the environmental conditions experienced at the time, in conjunction with any forces resulting from connected mooring lines.

For the purposes of bollard pull analysis, it has been assumed that the governing environmental condition will be the 10-year return storm with 1-minute average wind. The environments for the irregular wave model tests include cases of white noise, 1-year and 10-year environmental conditions, refer to Tables 4 & 5. There are a total of 8 different environmental combinations of waves, wind, and currents.

Table 5: Met-Ocean Data: Current Profile

	1-Year Seastate		10-Year Seastate	
Scale	Full	Model	Full	Model
Depth	Vc(m/s)	Vcm (m/s)	Vc(m/s)	Vcm(m/s)
Surface	0.9	0.1076	1.0	0.1195
Mid-depth	0.9	0.1076	1.0	0.1195
Bottom	0.8	0.0956	0.9	0.1076

The predominant environmental conditions are:

- Swell from a heading N to NE
- Wind from a heading of N to NE
- Current from a heading of W to NW (inline)

It should be noted that the tides are diurnal and the tidal direction will change 4 times a day.

The modeling of irregular waves in the wave basin is carried out based on the specified significant wave height, peak wave period and wave spectrum. The specified current speed near water surface is calibrated by means of adjusting the current generating system and the velocity is measured by a micro acoustic Doppler velocimeter. The effects of wind are simulated with an earth-fixed array of computer-controlled fans.

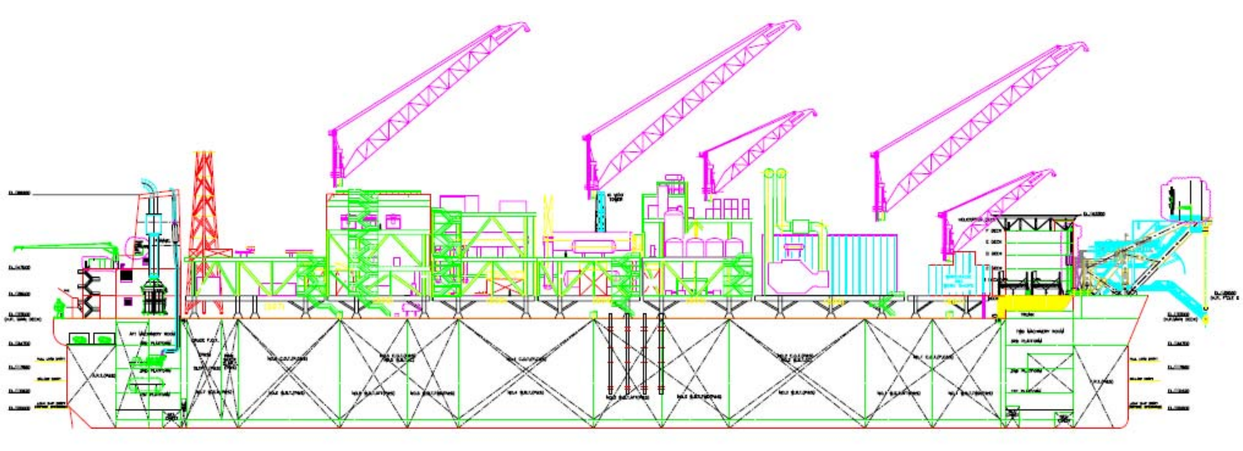

Fig. 3: Elevation View of the FPSO

Model Test

The scope of the model test covers the moment the FPSO arrives in the field until the installation of 14 jumpers and 4 cables. Intermediate stages include a positioning trial, positioning keeping and temporary mooring to the pre-installed SYMS mooring tower, pendulum mating, and ballasting to storm-safe. Due to the shallow-water effect of the VLCC FPSO and the complexity of the SYMS connection mechanics, it is difficult to use numerical tools to accurately analyze the hydrodynamic interaction between the FPSO and the SYMS, especially the multi-body interaction between the FPSO and the small installation vessels berthed along. Refer to Ref. [1] & [2] for details. The main purpose of the model test is to accurately assess dynamic responses of the FPSO and installation vessels during various stages of the FPSO hookup operation. Specific objectives include the following:

- Verify whether the proposed positioning spreads have adequate bollard pull capacity to keep the FPSO in position.
- Establish maximum loads in the FPSO mooring and positioning rigging components, as well as the mooring loads of the installation vessels.
- Size all the mooring and positioning rigging components.
- Determine maximum excursions during various stages of the FPSO hookup.
- Determine maximum motion responses of installation vessels during various installation stages.
- Establish environmental limits and operational sea states for each installation stage.

Due to the large size of the FPSO, a scale ratio of 1:70 was adopted in the model test, thus yielding a 0.394m water depth in the model test while the actual water depth is 27.6 m in prototype. The duration of each irregular wave test is equivalent to three-hour prototype installation simulation. The methodology and results of the model test are presented here and their findings will be used to guide the installation design at different phases of the FPSO mating operation.

The instruments are carefully calibrated prior to the commencement of experiment, which include the following:

- Non-contact optical motion measuring system for measuring the 6 degrees of freedom motions, i.e. surge, sway, heave, roll, pitch and yaw, of the FPSO model.
- A micro acoustic Doppler velocimeter for measuring the current speed.
- A hot wire anemometer for measuring the generated wind velocity.
- Several wave probes of resistance type for measuring the generated wave elevation.
- Four force transducers for measuring the axial forces on 4 mooring lines.
- Three angular transducers for measuring the angles.
- Two video cameras for recording all motions during tests.

Table 4: Environmental Conditions for Model Test

Env.	Wave (JONSWAP)					Wind		Current		Direction	Comment
	Full	Full	Model	Model		Full	Mode;	Full	Model		
No.	Hs	Tp	Hsm	Tpm	γ	Vw	Vwm	Vc	Vcm		
(-)	(m)	(s)	(m)	(s)		(m/s)	(m/s)	(m/s)	(m/s)		
1	4.9	9.3	0.0700	1.1116	3.0	22.0	2.6295	1.0	0.1195	Collinear	10-year storm
2	4.9	9.3	0.0700	1.1116	3.0	22.0	2.6295	1.0	0.1195	Crossed	10-year storm
3	3.3	7.7	0.0471	0.9203	3.0	17.0	2.0319	0.9	0.1076	Collinear	1-year storm
4	3.3	7.7	0.0471	0.9203	3.0	17.0	2.0319	0.9	0.1076	Crossed	1-year storm
5	2.5	-		-	-	-	-	-	-		White Noise
6	2.0	6.5	0.0286	0.7769	-	12.0	1.4342	0.9	0.1076	Collinear	2.0
7	1.5	5.5	0.0214	0.6574	-	12.0	1.4342	0.9	0.1076	Collinear	1.5
8	1.0	5.0	0.0143	0.5976	-	12.0	1.4342	0.9	0.1076	Collinear	1.0

Table 6: Principal Particulars of FPSO Prototype and Model

Designation	Symbol	Unit	Full scale	Model Scale	Full Scale	Model Scale
Length between perpendiculars	LBP	m	313	4.4714	313	4.4714
Breadth	B	m	63	0.9000	63	0.9000
Depth	D	m	32.5	0.4643	32.5	0.4643
Draft at FP	T_{FP}	m	14	0.2000	10	0.1429
Mean Draft	T_M	m	14	0.2000	11.5	0.1643
Draft at AP	T_{AP}	m	14	0.2000	13	0.1857
Displacement	Δ	Te	272580	775.31	223235.6	634.9587
Center of gravity	LCG	m	-1.02	-0.0146	20.08	0.2869
Center of gravity above keel	KCG	m	20.29	0.2898	149.51	2.1359
Roll Radius of Gyration	K_{XX}	m	22.03	0.3147	25.83	0.3690

Pitch Radius of Gyration	K_{YY}	m	77.49	1.1070	74.13	1.0590
Yaw Radius of Gyration	K_{ZZ}	m	80.18	1.1454	77.5	1.1071
Heave natural period	T_{Heave}	sec	14.3	1.7092		
Roll natural period	T_{Roll}	sec	17.6	2.1036		
Pitch natural period	T_{Pitch}	sec	13.1	1.5657		

Table 7: Prototype Particulars of Mooring lines

			Line property						Fairlead coordinates			Padeye at SYMS coordinates		
Line	Position	Attached to	Diameter [mm]	Length [m]*	Weight [kg/m]	Stiffness [MN/m2]	A [m2]	EA [MN]	X [m]	Y [m]	Z [m]	X [m]	Y [m]	Z [m]
1	Bow PS	Tug 1	72	500	3.05	27000	0.0041	109.9305	156.12	22.91	33.0			
2	Bow SB	Tug 2	72	500	3.05	27000	0.0041	109.9305	156.12	-22.91	33.0			
3	Stern SB	Tug 3	60	500	2.18	27000	0.0028	76.3406	-160.32	-23.41	33.0			
4	Stern centre	Tug 4	72	500	3.05	27000	0.0041	109.9305	-160.32	-7.15	33.0			
5	Stern PS	Tug 5	60	500	2.18	27000	0.0028	76.3406	-160.32	10.68	33.0			
6 ML 1	Bow SB	SYMS PS	80	58.3	3.52	27000	0.0050	135.7167	159.81	-15.49	33.0	210.5	12.5	40
7 (ML 2)	Bow PS	SYMS SB	80	58.3	3.52	27000	0.0050	135.7167	159.81	15.49	33.0	210.5	-12.5	40

Table 8: Model Particulars of Mooring lines

			Line property				Fairlead coordinates			Padeye at SYMS coordinates		
Line	Position	Attached to	Diameter [mm]	Length [m]	Weight [g/m]	EA [kg]	X [m]	Y [m]	Z [m]	X [m]	Y [m]	Z [m]**
1	Bow PS	Tug 1	1.0286	7.1429	0.6073	31.8834	2.2303	0.3273	0.4714			
2	Bow SB	Tug 2	1.0286	7.1429	0.6073	31.8834	2.2303	-0.3273	0.4714			
3	Stem SB	Tug 3	0.8571	7.1429	0.4340	22.1412	-2.2903	-0.3344	0.4714			
4	Stem centre	Tug 4	1.0286	7.1429	0.6073	31.8834	-2.2903	-0.1021	0.4714			
5	Stem PS	Tug 5	0.8571	7.1429	0.4340	22.1412	-2.2903	0.1526	0.4714			
6 (ML 1)	Bow SB	SYMS PS	1.1429	0.8329	0.7008	39.3622	2.2830	-0.2213	0.4714	3.0071	0.1786	0.5714
7 (ML 2)	Bow PS	SYMS SB	1.1429	0.8329	0.7008	39.3622	2.2830	0.2213	0.4714	3.0071	-0.1786	0.5714

FPSO Model: The general arrangement of the FPSO is shown in Fig. 5. The model is made of wood with weight elements to achieve sufficient accuracy of inertial properties. The model was constructed with sufficient rigidity and watertight proof. The weight in air, position of center of gravity and radius of gyration are adjusted on the FPSO and barge model by adding and shifting weight elements so as to meet the specified requirements. The particulars of the FPSO prototype and model are listed in Table 6.

Fig. 5: Models of the FPSO and SYMS System

SYMS Model: The model of the SYMS is manufactured on the basis of the design drawing shown below according to the model scale ratio of 1:70. Refer to Fig. 6 for details.

Mooring Lines: The five mooring line connecting tugs and FPSO, as well as the two crossing lines linking the SYMS turret and FPSO bow, are modeled. The particulars of lines are listed in Tables 7 & 8.

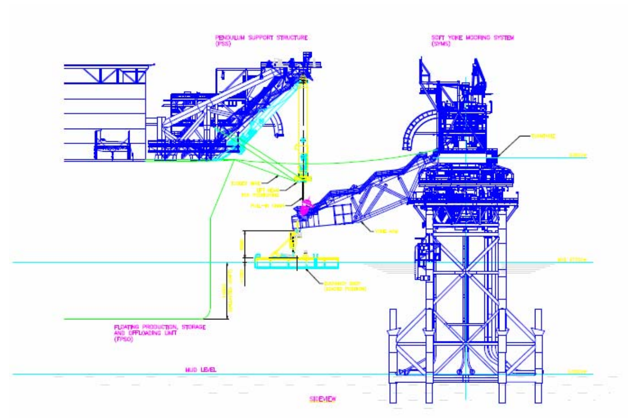

Fig. 6: Elevation View of the FPSO & SYMS

Law of Similarity: The similarity of the gravitational properties and inertial properties is satisfied, thereby maintaining the same Froude Number and Strouhal Number of the model and prototype as follows:

$$\frac{V_M}{\sqrt{gL_M}} = \frac{V_P}{\sqrt{gL_P}} \quad \text{and} \quad \frac{V_M T_M}{L_M} = \frac{V_P T_P}{L_P}$$

Where V, L and T represent characteristic velocity, length and period of the vessel motion, respectively. The subscripts M and P denote the variables for the Model and Prototype respectively. The viscous effect is ignored for the motions of vessels or offshore structures in waves.

Based on the law of similarity mentioned above, the relationships of particular variables between the Prototype and Model are listed in Table 9, where λ is the linear scale ratio and γ is the specific gravity of seawater (γ = 1.025).

Table 9: Variables between the Prototype and Model

Particulars	Particular Ratio	Scale Ratio
Length	L_P / L_M	λ
Velocity	V_P / V_M	$\lambda^{1/2}$
Rotation Angle	ϕ_P / ϕ_M	1
Motion Period	T_P / T_M	$\lambda^{1/2}$
Area	A_P / A_M	λ^2
Volume	∇_P / ∇_M	λ^3
Moment of Inertia	I_P / I_M	$\gamma\lambda^5$
Force	F_P / F_M	$\gamma\lambda^3$

Results of Model Test: The uni-direction irregular waves are generated by the dual flap type hydraulic wave maker. Wave probes of resistance type at specified locations provide measurements of generated wave elevation. The current is generated by the current generating system of high-pressure water jets. The wind is generated by means of wind generating system with an earth-fixed array of computer-controlled fans which are fixed at the location in front of the FPSO model for a distance of about 3m. Six tension transducers are mounted on the horizontal mooring lines and crossing lines. Three angular transducers are mounted on the turret and two yoke arm. Wave Probes #1 & #2 are installed at the locations in front and adjacent of the FPSO model. All the measuring instruments have been calibrated before the actual model test runs.

Tables 10 & 11 list the matrixes for the pre-mating and post-mating test runs, respectively, refer to the following:

Table 10: Pre-Mating Test Run Matrix in Wave Basin

Test No.	Weather	Env.	Direction	Remark
080901	10-year	#1	Collinear	5 tugs, be fixed
080903	1-year	#3	Collinear	5 tugs, be fixed
080901A	10-year	#1	Collinear	5 tugs
080902A	10-year	#2	Crossed	5 tugs*
080903A	1-year	#3	Collinear	5 tugs
080904A	1-year	#4	Crossed	5 tugs*
080905	10-year	#1	Collinear	2 tugs+2 cross lines
080906	10-year	#2	Crossed	2 tugs+2 cross lines
080907	1-year	#3	Collinear	2 tugs+2 cross lines
080908	1-year	#4	Crossed	2 tugs+2 cross lines

*Note：The test is not carried out because the FPSO Model can not be restrained in the wave basin.

Table 11: Post-Mating Test Run Matrix in Wave Basin

Test No.	Condition	Env.	Direction	Remark
080909	10-year	#1	Collinear	Empty Yoke
080910	10-year	#2	Crossed	Empty Yoke
080911	1-year	#3	Collinear	Empty Yoke
080912	1-year	#4	Crossed	Empty Yoke
080913	10-year	#1	Collinear	Mating
080914	1-year	#3	Collinear	Mating
080915	10-year	#1	Collinear	w/o FPSO
080916	10-year	#2	Crossed	w/o FPSO
080917	White Noise	#5	180deg	w/o FPSO
080918	White Noise	#5	180deg	w/o FPSO Cross Current 1.0m/s
080919	White Noise	#5	180deg	w/ barge
080920	White Noise	#5	135deg	w/ barge
080921	--	#6	Collinear	w/ barge
080922	--	#7	Collinear	w/ barge
080923	--	#8	Collinear	w/ barge

For position tests, the test set-up of the FPSO model and 5 tugs in irregular wave tests for collinear and crossed seas is shown in Figs. 7 & 8. In Case 080901 the tugs are fixed while in Case 080901A the tugs can be moved with the FPSO if the pull forces in tug more than 157Te. The bow tugs are 5 deg off the centreline while the stern quartering tugs are 10 deg off the centerline.

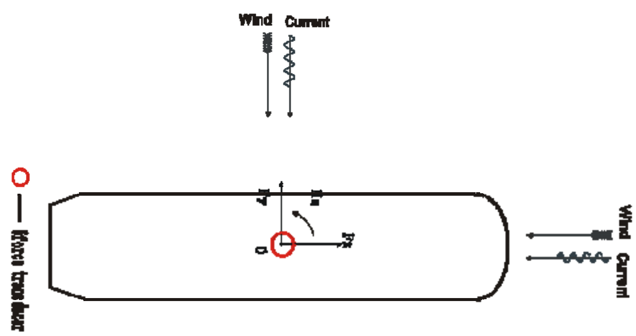

Fig. 7: Set up of Wind and Current Load Calibration Tests

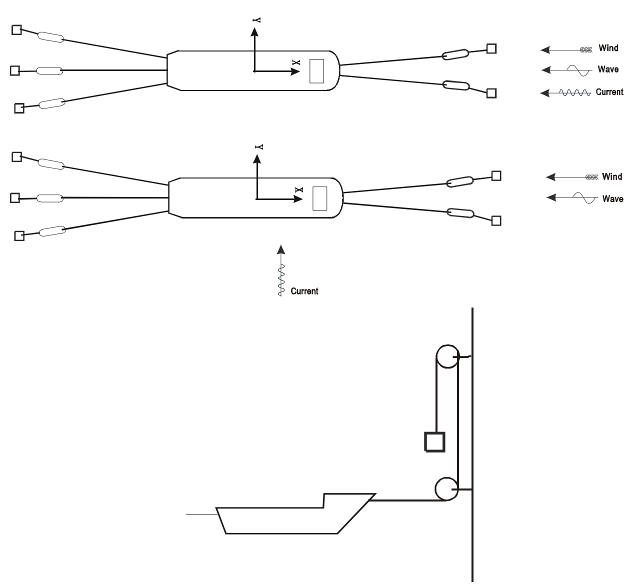

Fig. 8: Set up of the FPSO Model with 5 Tugs

Upon setting up the model at the specified position in the wave basin, all the instruments are mounted at the specific locations and calibrated to zero values. Due to the current action, the model drifts to a certain stable position. Then the computer-controlled fans generate the fluctuant wind while the wave maker generates the specified irregular waves. The data acquisition system then starts to measure the required data after motions of the model reach steady state. The results of the measured wind loads in head and beam directions for the FPSO will match with the target values obtained from previous Bluewater's test results.

All measurements are recorded on the computer with a sampling rate of 20Hz and a physical filtering frequency of 20 Hz. The analog-to-digital signal conversion is processed by an A/D converter. The measuring duration lasts more than 21.6 minutes in model scale, equivalent to 3 hour prototype time for each irregular wave test.

All the results of model test have been converted into the prototype scale. The time-domain test results are presented in statistic tables, including mean values, standard deviation, minimum and maximum values, positive significant, negative significant and double significant values. The results of all data analyses have been presented in both graphical and tabular format in the prototype scale. The scaling of force and mass includes the ratio between the specific weights of sea water and fresh water in the basin (γ = 1.025). The natural period and non-dimensional damping coefficient are derived from each measured decay test curve. The results of a typical decay test are presented in graphical format, see Fig. 9. Table 12 shows a typical test run result in tabular format. Refer to Ref. [3] & [4] for more details of the test results.

Table 12: Statistic Results of Test Run 080903

Test No. 080903

Result of Time Domain Statistic Analysis

1-year storm, Collinear, 5 tug; Hs=3.3m, Tp=7.7s; Vw=17m/s; Vc=0.9m/s

Chn	Title	Unit	Max	Min	Mean	Std.	Pos.Sign.	Neg.Sign.	Dou.Sign.
1	WaveE	m	3.896	-3.201	0.000	0.799	1.682	-1.518	3.109
2	WaveN	m	4.436	-3.291	0.000	0.896	1.880	-1.726	3.504
3	Surge	m	-2.248	-9.142	-4.958	1.005	1.559	-1.804	2.976
4	Sway	m	27.748	-18.809	3.213	10.409	20.804	-17.255	27.335
5	Heave	m	0.454	-0.487	-0.011	0.177	0.096	-0.077	0.145
6	Roll	deg	0.304	-0.261	0.013	0.079	0.155	-0.149	0.288
7	Pitch	deg	0.255	-0.173	0.020	0.055	0.074	-0.068	0.114
8	Yaw	deg	7.326	-6.972	-0.716	2.956	6.103	-5.108	10.430
9	F.line1	t	167.95	36.35	94.22	16.92	12.64	-14.17	22.48
10	F.line2	t	182.40	26.42	88.46	20.97	12.90	-12.21	22.12
11	F.line3	t	90.43	0.40	24.71	10.85	14.36	-13.57	22.98
12	F.line4	t	55.69	0.04	15.18	6.32	14.38	-7.59	19.48
13	F.line5	t	63.32	7.59	21.43	6.10	11.09	-6.50	14.65

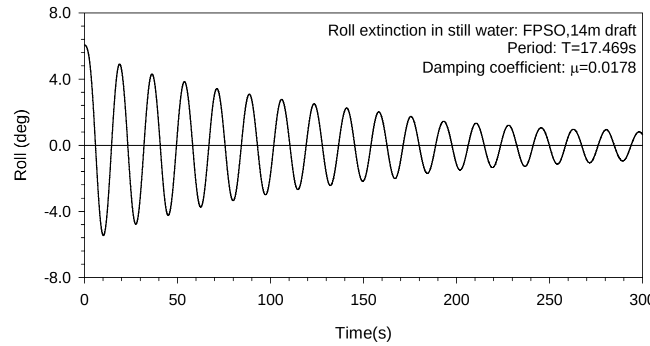

Fig. 9: Results of Roll Decay Test in Still Water (14m draft)

Virtual Simulation

A virtual simulation of the mating operation between the FPSO and the SYMS was performed at the STC BV Simulator Facility in Rotterdam, the Netherlands, thus providing a training and assessment program for the FPSO approach to the SYMS, the connecting of the mooring lines, station keeping whilst the pendulums are hooked up to the SYMS, bringing the work barge alongside of the FPSO, as well as contingency measures. This paper will give an overview of the simulations that were carried out and what lessons were learnt during five successive days from June 23 until June 27, 2008.

The objective of the simulation is to accurately replicate the offshore mating operation and identify any shortcomings of Installation Contractor's and/or Companies personnel and/or execution plan or systems. The simulation will also serve to familiarize all personnel involved with the FPSO, mooring tower and scope of work. The latter includes, moving and maintaining position of the FPSO during station keeping, pre-mooring and mooring pull-in and fastening. Such simulations will be carried out under normal conditions as well as under a number of stressful conditions, i.e. sudden adverse weather conditions, black out of primary tugboat, deadly accident, breaking of mooring lines, etc.

The key issue within this training program is the performance of the personnel executing the work. This is being analyzed and measured. The practical realistic interactive simulator scenarios were developed and validated in close co-operation with the appointed representatives before the beginning of the training and assessment program. Neither the technical model of the FPSO, modeled tugboats or vessels involved, nor the performance of the simulation facility is the subject of testing.

The findings of the simulations help make conclusions and recommendations on the aspects of both marine operations and the human behavior. The training and assessment program includes all the parties and key persons involved during the execution of the project. The models that were used during the training will be discussed. An overview of all observations done during the training and comments given during the debriefing sessions will be presented. The skills of the positioning and tug masters were assessed. The methodology that was applied to these assessments will be described.

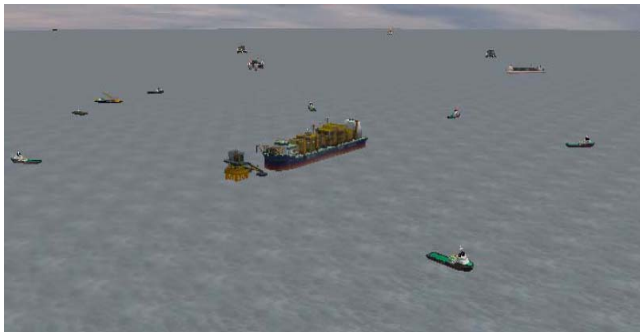

Fig. 10: Virtual Reality for the FPSO & SYMS Mating Operation and the Surrounding Facilities

Simulator facility: For this project STC developed mathematical models as well as graphic images of the FPSO, mooring tower, tugboats, barges and other objects in the field. Together with realistic environmental conditions a number of near "close to real-life" situations were created, see Fig. 10. Testing, assessing and measuring were carried out during five successive days in the end of June, 2008. The field layout was implemented in the simulator for the operator screens and visual area database.

During the actual offshore operation, a position monitoring system was used manufactured by Fugro Spatial Systems giving continuous feedback regarding the exact position and orientation of the FPSO. The positioning operation will be controlled from the Positioning Control Room, which will be the Helo Lounge located on Deck E on the starboard side forward on the FPSO below the Heli-deck. A survey positioning control system will be installed on the FPSO in the Helo Lounge on. This will be utilized throughout the operation to give real time position and heading information on the FPSO and Tugs.

Fugro personnel were on hand at the STC Facility to assist in the assembly, set up and fine tuning of these systems. On every bridge (FMB1 through to FMB4) FUGRO installed a positioning system that was used during all exercises. A screenshot of this display is given in Fig. 11.

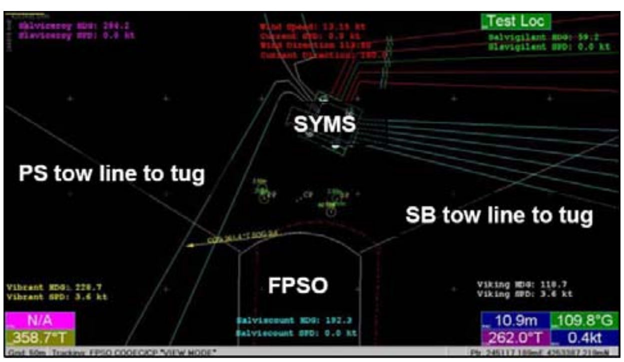

Fig. 11: Display of Fugro Positioning System

To simulate the mating operations, the following STC facilities were used:

- 360 degrees view Full Mission Bridge Simulator (FMB1) (tugboat), see Fig. 12
- 2 × 240 degrees Full Mission Bridge Simulator (FMB2 and FMB3) (2 Tugboats), see Fig. 13.
- Operator controlled simulator (FPSO, SYMS and 2 vector tugs) (FMB4)
- Positioning control room

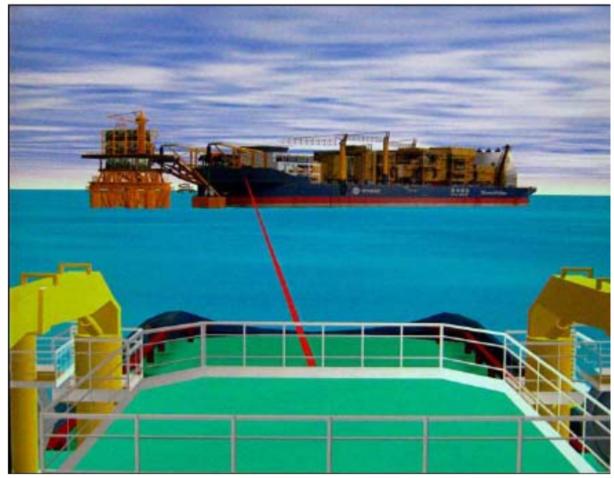

Fig. 12: From View of Tug 1 when FPSO Mating

All tug masters and positioning masters were able to communicate via an internal VHF network. All simulator operators could communicate via an internal VFH net on another channel.

All simulations were coordinated by an offshore expert and STC operators, with technical support from the research and development department and technical department when necessary. Only the tug masters and positioning masters were allowed to enter the bridges and mooring control room. All other observers could follow the positioning procedures in the control room of FMB1. In this control room the FUGRO display was projected on a large projection screen.

Fig. 13: Tug Master in Action

Simulator Models: For the simulator training mathematical and visual models were developed. The characteristics of these models are described here and, where necessary, some compromises were made due to simulation restrictions.

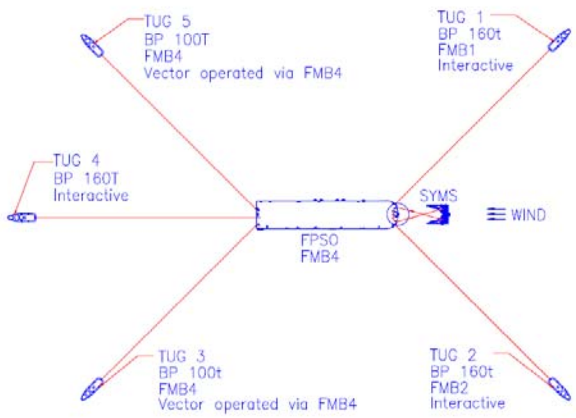

Fig. 14: Overview for Simulation Setup

There were 5 tugboats in total making up the mooring spread with the FPSO. Three of these tugs were interactive tugs and the other two were vector tugs. The FPSO was simulated on FMB4 and the 2 vector tugs were operated from FMB4 by STC personnel on the command of the Positioning Master. Each of the other Full Mission Bridge simulators represented an interactive tugboat where the positioning masters and the tug masters were maneuvering the tugboats. Tug 1 was controlled on FMB1, Tug 2 on FMB2 and Tug 4 on FMB3. The FPSO was simulated on FMB4. The rotating upper part of the SYMS was modeled as a traffic ship and was free to turn around the fixed lower tower structure under influence of wind, waves and current or external forces such as tension in mooring lines. An overview of the complete mooring spread setup is given in Fig. 14.

FPSO Model: A mathematical model is made of the FPSO unit for the towing and mating operation. During the positioning phase the draft of the FPSO is 14 meters. With a water depth of 27.7 meter, this results in a keel clearance of 13.7 meters for the operation in the Bohai bay. Regarding the mooring configuration FPSO-SYMS, from the bow of the FPSO two vertical pendulums are hanging, protruding about 18 m in front of the bow and 19 m from the centre line. Ultimately these pendulums are fixed to the SYMS after installation is completed. Mounted on the bow of the FPSO are two fairleads from where two cross mooring lines will initially connect the FPSO to the SYMS via the two pad eyes mounted on the SYMS. Refer to Table 1 for an overview of the most important characteristics of the FPSO.

The STC modeling software is primary developed for modeling ships and less for modeling floating constructions. This means that not all current force coefficients as supplied via the model test results could be included exactly in the simulator model for every angle of attack. In reality when homogeneous current is from the beam, the yawing moment may be neglected. If this is implemented the STC model, the FPSO will also not start yawing when the current angle of attack is 45 degrees. When the yawing moment is included in the model for an angle of attack of 45 degrees, the yawing moment for angle of attack of 0-degrees will be overestimated in the model. A compromise had to be made to handle this problem. Because wind forces are dominating, it is allowed to make this simplification. An extensive range of current force coefficients of the FPSO hull adopted from the towing tank tests was implemented in the simulator.

Wind tunnel tests were conducted to estimate the wind coefficients for the FPSO and thereby produced an extensive range of wind force coefficients. These coefficients were included in the simulator model without making modifications. Such modifications where not necessary because the wind force model in the simulator has exactly the same coefficients format as the results produced by the wind model tests. The wind coefficients from to the wind tunnel test data were implemented in the simulation. The wind is modeled by using a Davenport variation. Some deviation in wind strength and wind direction is taken into account in the simulation.

SYMS Model: The SYMS consists of a fixed lower base unit and a turntable. Two yoke arms are connected to the turntable, with a buoyancy tank at the end. Pendulums from the FPSO will be connected to the yoke arms. Two pad eyes are constructed on the SYMS to connect the hawsers from the FPSO. The tension in the mooring lines can be decomposed into a radial force and a tangential force component. The tangential component will generate a rotating moment acting on the SYMS where there is an arm from the pad eye to the rotation center. The SYMS will only start to rotate when a certain threshold value due to friction is exceeded while there is no damping effect. Refer to Table 2 for the technical characteristics of the SYMS.

Attendees: In order to accurately simulate the work that is going to be completed offshore, the following personnel were present:

- Positioning Manager, Positioning Masters, and Tug Masters
- Installation Manager, Superintendents, and Engineers
- Positioning Engineers & Positioning surveyors

Tests and measurements were related to all personnel participating, indirectly and directly including all company and installation contractor operation procedures, execution plans and systems such as emergency response, change management procedures, risk assessment and Job Safety Analysis procedures.

A large proportion of individuals involved in the FPSO Hookup are Chinese Nationals, potentially with a lack of English language skills. Communication problems due to language barriers are very difficult to overcome. To identify and possibly decrease these language communication problems, two Chinese speaking interpreters were active in some of the simulation exercises including briefing, training and debriefing sessions.

Debriefing: During the training and assessment week all exercises were evaluated by conducting debriefing sessions. For use during these debriefing sessions, debriefing software was available to show the position of all tugs and the FPSO at any moment during the exercise directly after the exercise was completed. Also the forces in the lines that occurred, environmental conditions and engine settings of the tugs could be reviewed after the exercise was completed. Based on daily contact with the Positioning Manager, it was sometimes decided that a particular debriefing session was not deemed necessary directly after the exercise itself and this was then was debriefed later on in the day together with another exercise.

A capable exercise coordinator experienced in offshore operations was assigned to debrief the training program and discuss the lessons learned during the exercises. This person was furthermore not affiliated with Client representatives or any of the subcontractors.

Training & Assessment: The training and assessment program include 17 training sessions to cover several kinds of scenarios as follows, refer to Ref. [5] for a complete training and assessment program:

- Station keeping in open water
- Approaching to SYMS and maintain position
- Mooring configuration testing
- Contingency scenarios like:
  a) Blackout of tug
  b) Breaking tow line
  c) Breaking hawser
- Barge approach and Communication Chinese – English operations

In order to maintain a realistic training environment, details of each training scenario were not openly discussed with the positioning and tug masters executing the work. The training briefings were therefore kept to a minimum. The exercises concerning station keeping in open water with five tugs were considered as an initial orientation exercise to familiarize participants with the facility itself, the bridges with its instruments and the models.

Assessments: From Tuesday to Friday a psychologist and a former tanker captain observed the actions of all positioning masters and tug masters. Every person was observed twice during the week for the duration of one hour. Results of these observations are presented in a confidential report of Management Notice Results Assessment. During all observation the exercises were videotaped. This material will be stored at the STC system for debriefing and future evaluation.

The confidential report presents the results of the assessment with respect to the individual performance of the Positioning Masters and an overview of the performance of the Tug Masters. The results/scores are the weighted averages of the independent observations of the assessors.

One Position Manager, four Positioning Masters and eight Tug Masters participated in the training and assessment program which is performed in a simulated work environment on board of the FPSO and the tugs. The assessment aspects include Information Gathering, Problem Solving Logic, Prioritizing, Working according a Plan or Directions, Decision Making Skills, Behavior Flexibility (Alternative scenarios in mind), Teamwork, Inspiring and Motivating, Stress Tolerance, Taking Initiative, Decisiveness, Feeling of responsibility, Communication Skill, Situational Awareness, Result oriented Leadership, Overall Performance, etc.

Lessons Learned: The actual execution of the training and assessment program went well. In general the exercises were clearly defined and executed. Time keeping during the whole program was an important point of focus and proved to be efficient and led to the reaching of the required goals. STC BV again showed her ability to assist in trouble shooting, e.g. problem with mooring line configuration between SYMS and FPSO, by thinking along with clients and assisting in finding and implementing a suitable solution, and also direct - on the spot - simulation thereof.

The lessons learned from the simulations are summarized as follows:

- The installation procedure of the FPSO and the SYMS should not be carried out if the wind exceeds 15 knots.
- In case of storm, it is possible to keep the FPSO under control, i.e. storm safe condition.
- Approaching the SYMS should always be done against the wind with a small angle between the FPSO heading and the wind direction.
- When using 3 tugs, i.e. head winds 13 knots, current 1 knot decreasing to 0,5 knots from NE, the mooring spread could be held in position (deviation around 1 ships length, i.e. 330 m).
- In case of a tug black out the other tugs seem to be able to keep the mooring spread in position.
- Tug black out can result in disabled tug colliding with FPSO, SYMS, other tug or tug wire(s).
- Tension meters should be installed on the hawsers and the actual tension values should be made known via Fugro system to position masters and tug masters.
- Doppler logs should be installed both on the bow and stern as also a Rate of Turn indicator. Values from Doppler and ROT should be made known to via Fugro system to position masters and tug masters.
- The FUGRO watch circles should be positioned on both pendulums instead of on the bow only.
- Showing the limiting tow line angles for each tug will assist in preventing possible collision between towline and SYMS or FPSO pendulums etc.
- The current mooring configuration should be reviewed because winching the FPSO towards the SYMS causes the SYMS to turn in an unfavorable (opposite) direction and makes mooring unnecessary difficult.
- Alternative crossed mooring lines connected together at their common crossing point, i.e. a two V-inverted mooring lines configuration, looks very promising as a solution to the current mooring system and seems practically relatively easy to implement.
- In case of a mooring wire break with the current mooring system, the SYMS will rapidly rotate and there may be danger of collision with FPSO or tug wire(s) or both. Tow masters must react very fast in order to counteract this as quickly as possible (best reaction is to unmoor ASAP).
- Tow masters to be especially vigilant during hook up procedures and be able to react extremely fast if need be.
- Chinese-English communication appeared to be rather difficult with a lot of talking in Chinese over the VHF. It appeared that there was quite some discrepancy between the receiver and the sender and that not all relevant information was being translated by the interpreter resulting in lack of clarity concerning the intensions of the barge and connected tug. Misunderstandings like this can lead to inefficiency or even accidents.

Conclusion

This paper presents the methodologies and findings of the model test and the virtual simulation for the FPSO Hookup, and also addresses how to apply their different findings to the installation design and the mating operation procedures between the FPSO and the SYMS in shallow water. The methodologies of the model test and the virtual simulation described here can be easily extended to the deepwater applications of various floating systems. It is certain that the model test and the virtual simulation will play more important role and have wide application in FPSO positioning and hookup operations, as well as offshore installation of SEMIs, SPARs, TLPs, etc. in deep water and ultradeep water.

Acknowledgements

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