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SPAR BUOY NUMERICAL MODEL CALIBRATION AND VERIFICATION

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Abstract. The present paper describes the experiences gained from the design methodology and operation of a 3D physical model experiment aimed to investigate the dynamic behavior of a spar buoy (SB) off-shore floating wind turbine (WT) under different wind and wave conditions.
The physical model tests have been performed at Danish Hydraulic Institute (DHI) off-shore wave basin within the European Union-Hydralab IV Integrated Infrastructure Initiative, in October 2012. The floating WT model has been subjected to a combination of regular and irregular wave attacks and steady wind loads. Observations of hydrodynamics, displacements of the floating structure, wave induced pressures and tensions at critical points of the structure and at the mooring lines have been carried out. Based on the observed data, the numerical model *Sesam* [1], developed by Det Norske Veritas (DNV), has been calibrated and verified. The adopted numerical model took into account the wave induced response and the effects of the mooring lines on the overall system.
The calibration of the numerical model has been performed both for static and dynamic conditions.
At the end of the calibration procedure, the numerical model has been successfully used to simulate two selected irregular wave attacks.

1 INTRODUCTION

During the last years the demand for energy consumption has increased worldwide. The recent interest on renewable energy devices has triggered the research and design of coastal and off-shore structures capable to produce energy from waves, currents and wind.

While the fixed WT technology can be considered mature, and many turbines have been installed in water depths up to around 25 m, it is recognized that to reach the objectives of renewable energy production it will be necessary to expand the technology for deeper waters adopting a floater as a support structure for off-shore WT; beyond 40 to 50 m water depth, it becomes economically advantageous to use a floater.

However, although the interest of the scientific community regarding the floating off-shore WT is developing quickly, the dynamic analysis of these structures still remains an unsolved and complex problem; consequently, the knowledge of the behavior of off-shore floating WT under a combination of waves and wind actions represents one of the most difficult challenges in offshore engineering.

Linear and higher-order diffraction and radiation forces imposed to the floating body, as well as the response of the mooring lines, determine a highly complex dynamical system.
For the above reasons, the determination of the design loads on offshore floating WT become a very tricky topic involving coupled wave and wind models [2], multivariate probability analysis [3, 4] and advanced load-calculation methods [5].

In the process of understanding the behavior of these structures, physical model tests are required, which represent another challenge by their self at any off-shore laboratory, mostly due to the difficulties encountered in the instrumentation of the body and the evaluation of the scale effects. Furthermore, as in the case of other topics in coastal and off-shore engineering, numerical modeling of the hydrodynamic behavior remains an attractive design and analysis approach [6], yet it requires the application of highly computer demanding models which in turn need model scale and/or prototype measurements for calibration and verification [7].

An overview of the numerical models able to perform integrated analysis coupling the dynamics among wave, structure and wind is provided by [8].

Although many studies, [9, 10] among the others, highlighted a good predictive capability of the adopted numerical models, they follow simplified modeling approach for the dynamic response of mooring lines systems, raising doubts on the predicted coupled hydrodynamic behavior. Recent studies have shown an improved modeling fidelity when the multi-body approach or the finite element methods are considered [11, 12].

2 PHYSICAL MODEL DESIGN OF THE SB FLOATING WT

The design of the physical model at reduced scale has taken the SB OC3-Hywind prototype [13, 14] as a reference.

The OC3-Hywind is a SB floating WT developed within the Offshore Code Comparison Collaboration (OC3). The OC3-Hywind system resembles the SB concept called "Hywind," developed by Statoil Hydro of Norway; it features a deeply drafted slender SB with 3 catenaries mooring lines. The lines attach to the platform by a delta connection (or "crowfoot") to increase the yaw stiffness of the moorings.

Table 1 summarizes the geometrical characteristics and the properties of the SB OC3-Hywind for both prototype and scaled (1:40 factor) model.

The floater of the SB model has been designed consisting of three main parts: an upper cylinder 300 mm long and having an outer diameter of 162.5 mm; further below, a 200 mm long structure made up of a vertical cone shape becoming wider up to a diameter of 235 mm; the remaining 2.6 m have been constructed as a main cylinder with a constant diameter of 235 mm, presenting a removable bottom 100 mm long which has been used to place the ballast. The SWL was at a distance of 300 mm from the top of the upper cylinder. The SB model has been ballasted using lead spheres and lead bars.

Table 1: Geometrical characteristics and properties of the SB OC3-Hywind. Model scale ratio (1/λ) = 1:40

SB OC3-HYWIND	Full scale	Unit	Scale factor	Scaled model
Platform Diameter Below Taper	9.4	m	λ	0.2350
Depth to the platform base below SWL (total Draft)	120	m	λ	3.0000
Platform Diameter Above Taper	6.5	m	λ	0.1625
Depth to Top of Taper Below SWL	4	m	λ	0.1000
Depth to Bottom of Taper Below SWL	12	m	λ	0.3000
Tower height	88.5	m	λ	2.2125
Hub level	90	m	λ	2.2500
Hub Diameter	3	m	λ	0.0750
Radius to fairleads	9.4	m	λ	0.2350
Radius to anchors	853.9	m	λ	21.3475
Depth to fairleads	70	m	λ	1.7500
Depth to anchors	320	m	λ	8.0000
CM location below still water level	89.9155	m	λ	2.2479
Unstreached line length	902.2	m	λ	22.555
Line diameter	0.09	m	λ	0.0023
Line mass density	77.71	kg/m	λ^2	0.0474
Angle between adjacent lines	120	deg	λ^0	120

The mooring system consisted of 3 mooring lines directly connected to the main cylinder using a collar with fairleads placed at 1.75 m below the SWL. The angle between 2 adjacent mooring lines was 120°. In the design of the SB model, a single mooring static analysis has been performed to obtain the initial fairlead angles and to determine the locations where to set the anchor plates. The analysis has been done by the code STATMOOR [15] which is capable to handle the static analysis of extensible mooring lines made of several segments each of them with different geometrical properties and with attached submerged buoys along them. The equilibrium position has been identified and the corresponding horizontal force component at the upper end (fairlead) has been determined.

As a consequence of limited water depth in the basin, for the experimental phase it was necessary to individuate a truncation point (pivoting point), for the static excursion curves of the catenary allowing to represent the longer chain by a short line having the correct configuration when the SB moved sideways. Truncation point was at a vertical distance of 1.25 m and at an horizontal distance of 1.94 m from the fairleads. Forces at the top of the 3 mooring lines have been observed by force transducers having a maximum load capacity of 30 kg. Following the force transducers, springs of 0.75 m length with spring coefficients of about 0.028 N/mm have been attached to the mooring lines. Each mooring line was made by a thin rope with a 1.7 mm diameter, a weight of 2.4 g/m, and an equivalent extensional stiffness of 6.25 N/mm. The mooring lines have been pre-tensioned with a weight of 1.5 kg per mooring line.

Figure 1 shows the SB scaled model installed into the wave basin.

Figure 1: Photograph of the SB model

At the base of the tower a 6 component force gauge measuring the forces F_x, F_y, F_z and moments M_x, M_y and M_z has been mounted. The tower was a slender plastic cylinder and had an outer diameter of 80 mm and a length of 161.5 cm. At the top of the tower a 4 components force gauge measuring F_x, F_y, M_x and M_y has been placed. At top of the 4 components force gauge, the nacelle has been installed. Furthermore, 3 accelerometers measured the accelerations at different levels along the tower; in particular, two accelerometers have been placed underneath the nacelle and a third one has been fixed at the bottom of the tower.
A motor inside the casing has induced the rotation for the rotor; a potentiometer adjusted the rotational speed. The rotation has been kept constant throughout the rotational tests at a speed of 38 rpm, which corresponds to a rotational speed of 12.1 rpm at the full scale, accounting for the gyroscopic effect.

Regarding the wind loads, only the mean thrust force has been modeled. The experimental set-up has consisted of a weightless line connected to the nacelle, passing through a pulley and with a suspended mass with weight equal to the target thrust force. The full scale thrust values have been calculated before by other researchers for the 5 MW NREL reference turbine, as for example by [16], who found that the rotor thrust under a 11 m/s wind speed is equal to about 800 kN. The additional thrust applied to the wind turbine has been constant as well with a force of 7 N in model scale. Further tests to obtain a relationship between thrust and rotational speed have been carried out with rotational speeds of 32 rpm, 38 rpm and 42 rpm at the model scale.

The rotor blades have been scaled geometrically; each blade had a length of 1.575 m. They have been constructed by using fiber glass and scaling the drawings from a real case. The pitch of the blades has been set to 30° determining a measured thrust of 4 N at 38 rpm at model scale. Table 2 summarizes the properties of the WT and the blades.

Table 2: Summary of properties of the WT, scale ratio (1/λ) = 1:40

WT	Full scale	Unit	Scale factor	Scaled model
Rotor mass	110000	kg	λ^3	1.6768
Nacelle mass	240000	kg	λ^3	3.6585
Rated rotor speed	12.1	rpm	λ^0	12.1000
Overhang	5	m	λ	0.1250
Shaft tilt	5	deg	λ^0	5.0000

3 PHYSICAL MODEL TEST SET-UP

3.1 Wave generation and basin instrumentation

The experiments have been performed at the DHI Offshore Wave Basin in Hørshom, Denmark. The wave basin is 20 m long and 30 m wide with an overall water depth of 3 m and a 6 m deep pit. The floating structure has been placed at the centre of the pit at a distance of 8 m from the wave maker, which lies at the 30 m wide side of the basin; in particular, assuming the origin of the local coordinate system at the right side of the wave maker, the model has been placed at x = 38 m and y = 15 m. The cross section area of the basin perpendicular to the wave direction is 600 m^2.

The wave maker is equipped with 60 individually controlled flaps capable of generating regular and irregular waves attacks. A parabolic wave absorber located opposite the wave maker minimized reflection. Incident and reflected waves have been obtained by a 5 wave gauges array reflection analysis [17]. The wave calibration procedure has considered the 5 gauges at the centre of the pit; during the model tests, they have been displaced at 3 m from the floating structure. In addition, 6 wave gauges have been located around the structure; they have been aligned at 1.5 m from the front side and from the rear side of the structure.

A Vectrino type velocimeter has been used to measure the velocity field in proximity of the structure.

A Qualisys Track System (www.qualisys.com) has followed the 6 degrees of freedom movements of the structure: translational surge, sway and heave, and the rotational roll, pitch and yaw. The system is accompanied by 2 cameras emitting infra-red light. The infrared light has been reflected by 5 passive spherical markers, having 40 mm diameter and positioned on a frame which has been mounted at the tower base just below the 6 components force gauge. Data processed by the Qualisys Track Manager have been directly transferred into an analogue output to the main data acquisition system and thus synchronized with all other recorded data.

All observed data have been synchronized by using the DHI Wave Synthesizer. All data have been sampled at 40 Hz for a single wave attack duration equal to 3 minutes for the regular wave case, and equal to 10 minutes, for the irregular wave case.

3.2 Tests programme

The model tests considered three meteo conditions (no rotation, normal operational and extreme). At first, the dynamic behavior of the floating structure has been investigated under no wind conditions. Afterward, normal operational conditions have been simulated with combined rotation (rated wind speed) and wave agitation. Finally, extreme wave conditions have been generated with the rotor being stopped (cut off wind speed).
The floating structure has been tested using long crested regular and irregular waves, orthogonal (0 degrees) and oblique (20 degrees) to the structure. The selected wave conditions values refer to typical storm conditions at both sea and ocean areas. In Table 3 the characteristics of the considered waves are reported, where H and T indicate the regular wave height and wave period, respectively, and H_s and T_p represent the significant wave height and peak wave period, respectively.

Table 3: Summary of properties of the WT, scale ratio (1/λ) = 1:40

Meteo conditions	Reg/Irr	Prototype H/H_s (m)	Prototype T/T_p (s)	Model H/H_s (cm)	Model T/T_p (s)
No wind and operational condition	Reg	1	10.1	2.5	1.6
		1.56	12.6	3.9	2
		1.80	15.2	4.5	2.4
		4	11.4	10	1.8
		6		15	
		12		30	
		6	12.6	15	2
			15.2		2.4
	Irr	4	10.1	10	1.6
		6		15	
Extreme conditions	Reg	10	11.4	25	1.8
		12	12.6	30	2
			15.2		2.4
	Irr	8	12.6	20	2

4 THE NUMERICAL MODEL

In the present study, the DNV GL's Sesam software has been adopted (www.dnv.com). Sesam (Super Element Structural Analysis Modules) is a complete strength assessment system for engineering applications capable to perform structural and hydrodynamic analysis based on the Finite Element Method (FEM).

Sesam consists of different modules. The modules used in the current study are:

- GeniE, a CAD tool for the design and analysis of offshore and maritime structures made of beams and plates.
- HydroD, an interactive program used to perform stability and wave loads analysis on fixed and floating bodies with or without forward speed.
- DeepC, a tool performing coupled analysis for mooring and riser design as well marine operations of offshore floating structures in the time domain.

The numerical investigation mainly concerned on:

- design of a proper geometry of the floater and the mooring lines and definition of the environmental loads (by GeniE);
- verification of the geometry stability through hydrostatic and hydrodynamic analysis (by HydroD);
- calibration of the numerical model via static and dynamic analysis of free decay tests (FDT) and regular waves (by DeepC);
- verification of the numerical model under irregular waves conditions (by DeepC).

The numerical simulations have been performed at prototype scale. The results of the calibration and verification of the model from selected representative cases are illustrated in the following.

4.1 Calibration

The calibration of the numerical model has been performed both for static and dynamic conditions. The static analysis has provided the pre-tension values of the mooring lines as well the position of the floating body at still water conditions. The dynamic analysis has provided the time series of the floater motions and the variation of the mooring lines tensions.

With regard to the static analysis, the FDT carried out during the physical model tests have been considered.

Table 4 summarizes the observed and calculated values of the natural periods/frequencies for surge, heave and pitch motions.

Table 4: Summary of the observed and calculated values of natural periods/frequencies for surge, heave and pitch

	Physical model		Numerical model	
	Period (s)	Frequency (1/s)	Period (s)	Frequency (1/s)
Surge (m)	88.5	0.011	85.5	0.012
Heave (m)	29.0	0.034	29.0	0.034
Pitch (°)	40.9	0.024	41.0	0.024

In Figure 2 the comparison between the observed and calculated values shows a good agreement for heave and pitch. A weak discrepancy is obtained for the surge, reasonably due to the superposition of the other motions.

With regard to the dynamic analysis, a selected orthogonal regular wave condition (H= 2.66 m and T= 11.39 s) has been considered.

Figure 3 and Figure 4 show the comparison between the observed and calculated values of translational (surge, sway and heave) and rotational (roll, pitch and yaw) motions, respectively.

A good agreement is found for the surge, heave and pitch cases. The observed sway assumed a constant value larger than 1 m. It makes evident that during the physical model tests the Qualisys Track System has been calibrated with a certain inaccuracy taking into account a value of about 2.5 cm (i.e. 1 m in full scale) with regard to the y-axis. The calculated yaw rotation is equal to zero, as expected. The behavior of the observed yaw rotation highlights a sort of asymmetry in the design of the physical model (floater or mooring system).

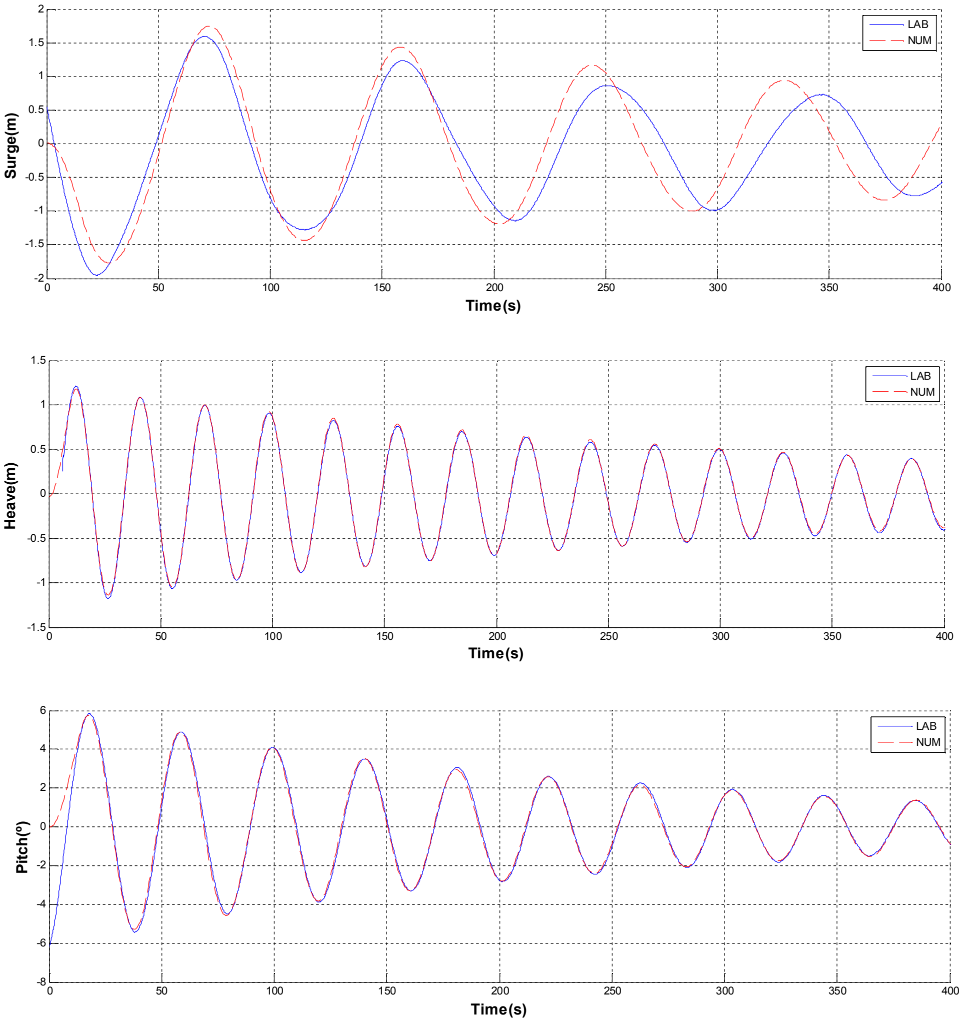

Figure 2: FDT time series. Comparison between observed (blu line) and calculated (red line) values

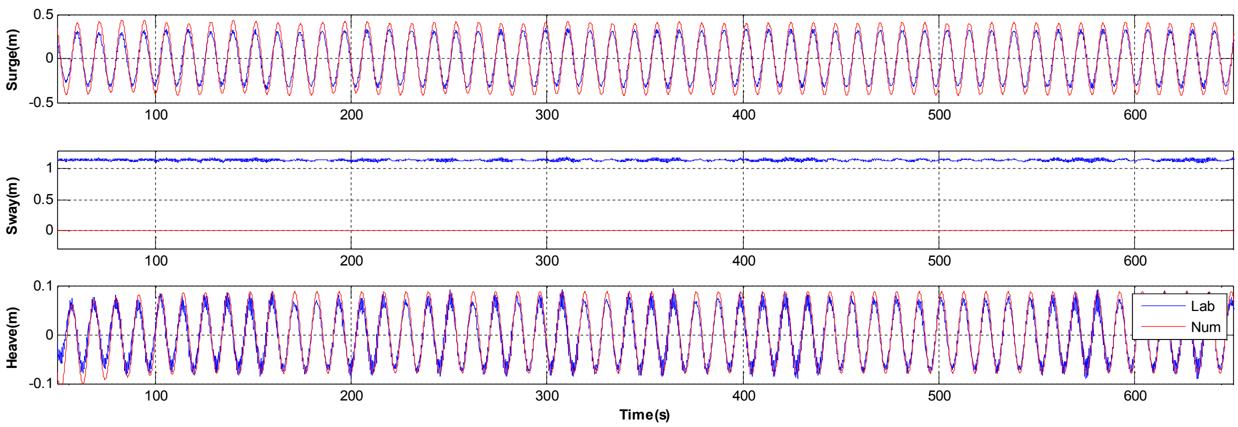

Figure 3: Test number T1380. Comparison between the observed (blu line) and calculated (red line) time series for the translational (surge, sway and heave) motions

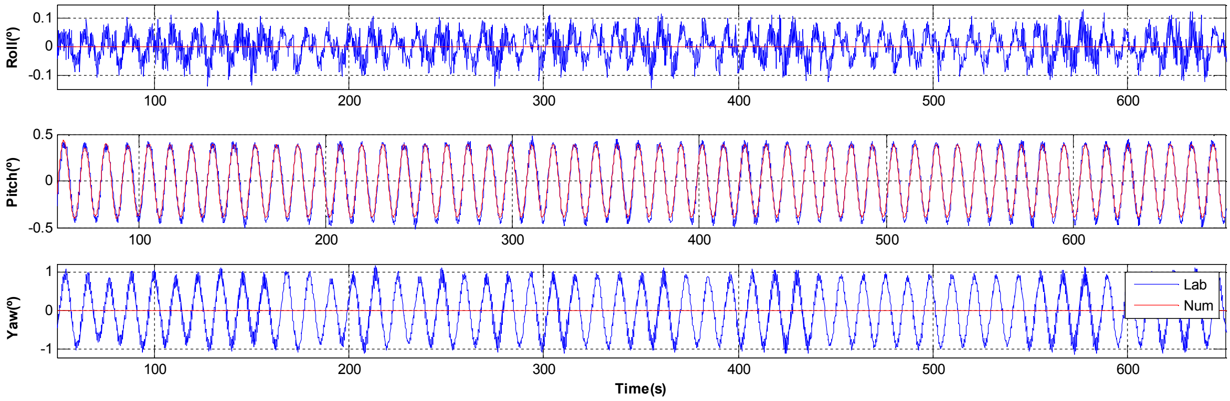

Figure 4: Test number T1380. Comparison between the observed (blu line) and calculated (red line) time series for the rotational (roll, pitch and yaw) motions

4.2 Verification

The verification of the performance of the calibrated Sesam model has been conducted with regard to two selected orthogonal irregular wave attacks. In the following, the results of the verification are presented for a representative case (H_s = 4.04 m and T_p = 9.81 s) solely.

Figure 5 shows the comparison between observed and calculated probability functions of surge, heave and pitch motions. A good agreement is found.

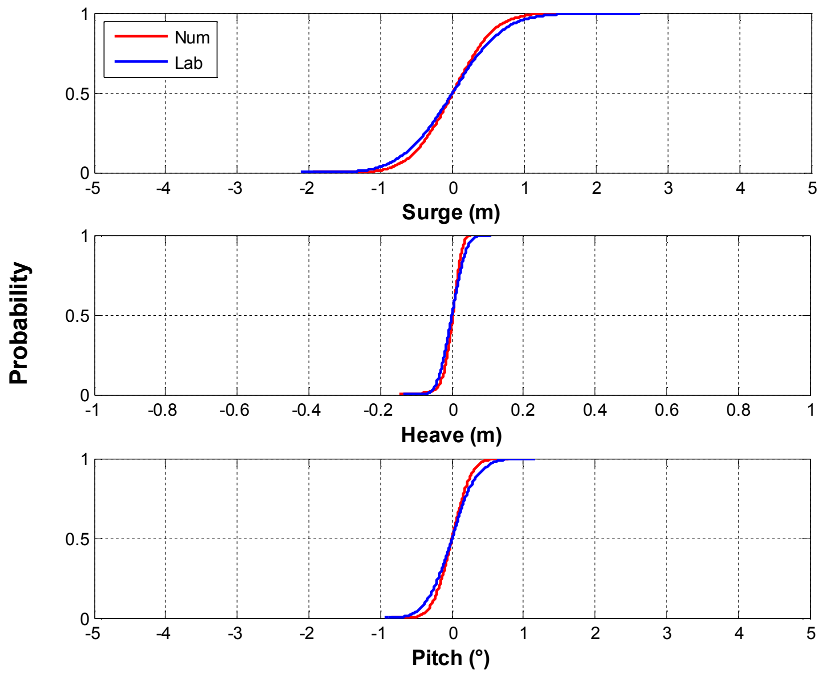

Figure 5: Test number T1380. Comparison between laboratory and numerical probability functions of surge, heave and pitch displacements

5 CONCLUSIONS

The recent interest in renewable energies has increased the demand of quality tests to optimize the design of innovative floating off-shore WT and to collect reliable and accurate data for further calibration and verification of numerical models.

As shown from other experimental works, to gain information on flow processes at structures and induced forces, the interpretation of the experimental data observations can give a paramount contribution toward the rational definition of the wave-structure interaction [18, 19]. As a consequence, the working features of floating off-shore WT need to be investigated through large-scale laboratory experiments and the off-shore laboratories are involved in the testing of new technologies and ideas, often subjected to disclosure restrictions and confidential issues.

The present paper has described the experience gained from the design methodology and operation of a 3D physical model experiment aimed to investigate the dynamic response of a SB type floating off-shore WT under different wind and wave conditions.

Detailed measurements of the amplitude of the motion of the floating body, acceleration, static and dynamic tensions at the mooring lines, the hydrodynamic flow field, the wave induced pressures and tensions at critical points of the structure have been carried out.

Based on the observed data, the numerical model *Sesam* has been calibrated and verified. In particular, the calibration of the numerical model has been performed both for static (FDT) and dynamic (under regular wave attacks) conditions.

With regard to the static condition, the comparison between the observed and calculated values showed a good agreement for heave and pitch. It resulted only a weak discrepancy for the surge, reasonably due to the superposition of the other motions.

It is noticed that, in general, FTD are carried out only for those motions which determine a hydromechanical restoring force or moment. It follows that the FDT have been performed in the presence of taut mooring lines; in this context, all the 6 DOF have been taken into account.

With regard to the dynamic condition, a good agreement between the observations and the calculated results has been found for the surge, heave and pitch cases.

At the end of the calibration procedure, the numerical model has been successfully verified against two selected irregular wave attacks.

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