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EXPERIMENTAL SET-UP FOR ANALYSIS OF SUBSEA EQUIPMENT INSTALLATION

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ABSTRACT

This paper and the companion paper (Rateiro et al., 2011) present an illustrative case of the joint application of experimental tests and numerical simulations for the proper analysis of a complex offshore operation (launching of a sub-sea equipment using one or two vessels). The main idea of the whole study is to compare two methodologies and operational procedures for the installation of the equipment in the seabed, using either one vessel (conventional operation) or two vessels in a synchronized operation in a Y-configuration. The experiment was conducted under a simplified configuration, and uses ODF (one degree of freedom) servo-actuator to emulate the vessels induced motion. The hydrodynamic properties of the equipment was then calculated, and some preliminary conclusions about system dynamics could also be drawn. After that, numerical simulations were conducted, considering the coupled dynamics of the vessels, cables and equipments under irregular sea state. Those simulations were used for determining the limiting environmental condition for a safe operation, and are described in the companion paper. This paper describes the reduced scale experimental setup used for evaluating the hydrodynamic properties of the equipment during a subsea installation under waves excitation. The reduced scale model of the equipment was attached to one or two servo-actuator, that emulate the wave-induced motion. The tests were conducted at the physical wave basin of Numerical Offshore Tank (Tanque de Provas Numérico - TPN). The experiments enabled the preliminary evaluation of the dynamic behavior of the equipment when submerged by one or two launching cables. In the later case (two launching cables), several tests considering phase shifts between the servo-actuator have been conducted. The reduction in the dynamic amplification of cable traction could also be experimentally verified.

INTRODUCTION

Subsea equipments such as manifolds require complex offshore operations to be launched and positioned in the correct location in the seabed. Rowe et al. (2001) presented several problems associated with subsea launching. The most relevant problems pointed by the authors are:

- Lifting equipments: problems associated with the loads to be lowered, dynamic amplification during the launching and capability of the equipments;
- Load control and positioning: problems associated with the correct final laying positioning of the subsea equipment;
- Weather conditions: problems associated with launching vessel induced motions and weather window to a safe operation.

The present and the companion paper (Rateiro et al., 2011) present a methodology to analyze complex offshore operations involving sub-sea installations. The execution of small-scale experiments involving all vessels and components of the actual operation may be extremely complex and expensive.

Furthermore, depending on the needs of the offshore industry, the time required to prepare and execute such experiments may not make the experiments feasible.

Numerical simulation is a tool that engineers use for performing analysis prior to actual installation. Ferreira (2002) presented an extensive numerical analysis of a conventional manifold installation procedure using a linear frequency domain analysis. In that work, the importance of the coupled dynamic analysis was stressed. An alternative launching method using two vessels was presented by Santos et al, (2009). Nonlinear time domain simulation was used for predicting the loads in the cables, but no dynamic coupling between vessels and the load has been considered. In those works, no experimental validations were presented.

However, due to the enormous complexity of some operations, the engineers cannot rely only on the numerical simulation results to make important decisions. A combination of numerical and experimental analysis was presented by Fernandes et al. (2006) for the evaluation of the pendulum method for subsea launching. This launching procedure requires one vessel and no environmental condition is considered. In that case, fundamental aspects of the experimental results were recovered by simulations, but rotational motions of the manifold could not be predicted. The results obtained in the analysis were important for the definition of the real operational installation procedure (Lima et al. 2008).

In Fujarra et al. (2008), an example of a hybrid methodology to analyze a complex subsea equipment installation was presented. Simplified experiments were used to validate the numerical simulations, which were then used for further complex simulations for the full-scale operation under real environmental conditions. The installation of a riser supporting equipment was considered. Due to the complexity of the equipment, during the installation, supplementary cables and two tug boats were employed. A full set of simplified and low-cost, small-scale experiments were carried out and the results were then used to validate a numerical model. Then, complementary numerical simulations were completed to consider extreme wave conditions and an irregular sea spectrum. The simulations indicated some operational problems that may occur during the installation, and the results were used to re-design specific steps of the procedure. The same design methodology is adopted in the present work.

This paper and the companion paper (Rateiro et al., 2011) present an illustrative case of the application of that design methodology for the comprehensive analysis of a complex offshore operation. The main idea of the study is to compare two methodologies and operational procedures for the installation of the equipment in the seabed, using either one vessel (conventional operation) or two vessels in a synchronized operation in a Y-configuration (Figure 1).

Simplified experiments were conducted, in order to verify the critical aspect of the conventional launching, concerning cable slackening and large dynamic traction amplification. The advantages of the Y-launching were then verified, since this amplification can be avoided by the proper positioning of the vessels. The experimental results were then used to calculate damping coefficient of the manifold, as well as to verify other important hydrodynamic coefficients. Hydrodynamic effects related of the proximity to the seabed were not studied in this work. The objective of this study was to verify the advantages of the Y-method during the descending motion. The final positioning of the manifold in the seabed will be studied later.

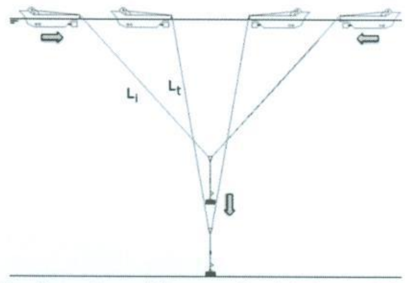


Figure 1. Y subsea launching method (adapted from Santos et al., 2009)

EXPERIMENTAL SETUP

In order to simulate the vessel induced motion and measure the load forces acting on it, a simple experimental setup was developed. The major components are two servo-actuators, a micro-controller to generate the sinusoidal motion reference, load cells to measure the cable loads and the manifold model.

The 400W servo-actuators impose vertical motion to the manifold. The total displacement range is 280mm with a resolution of 50μm (Figure 2). It is important to stress that the vertical wave induced motion is the only responsible for cable slackening and load amplification, as will be explained latter.

Horizontal wave induced motion excites the pendulum oscillation of the manifold with small amplitude since the natural frequency of the pendulum motion is much smaller than wave frequency.

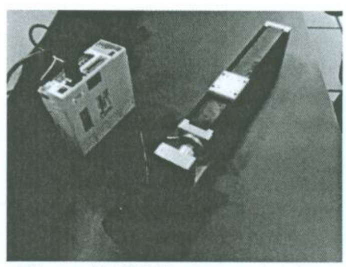


Figure 2. ODF servo-actuator.

In order to synchronously generate the sinusoidal trajectories in the two ODFs servo-actuators, a Renesas R8C/1B microcontroller was used, executing a real time temporization software. A RS-232 connection with a PC was also deployed to configure and parameterize the microcontroller. The parameters that could be changed are: frequency, amplitude, number of cycles and relative angle (phase shift) between the actuators. A fade-in and fade-out feature is also included in order to prevent abrupt motions that impose high loads to the experimental setup.

A load cell is attached to the moving base of each actuator for measuring the cable load. It was taken into account that the mechanical parts connected to the load cell didn´t produce any friction and vibration that propagate to the load measurements. HBM S2-100N load cells, with maximum load of 100N, were used. The arrangement is show in Figure 3.

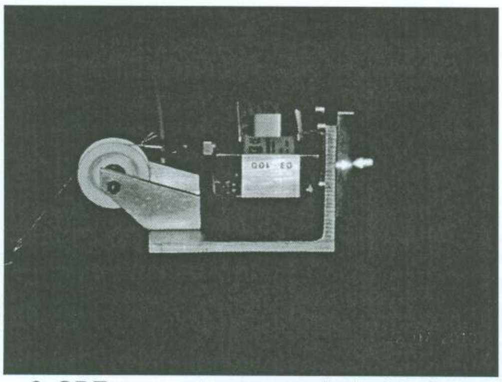


Figure 3. ODF servo actuator attached with the load cell and cable.

The acquisition system is a HBM MX-840, controlled by the same PC that operates the actuator´s microcontroller. The sample frequency used was 50Hz and the low-pass filter cutoff frequency is 25Hz. The electrical setup is shown in Figure 4.

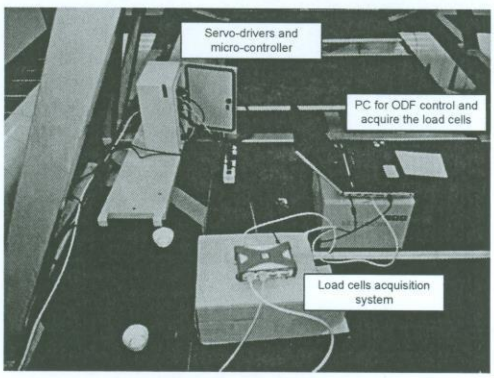


Figure 4. Setup of the electrical parts.

The Manifold model is a box shape with Froude scale factor equal to 1:35. The dimension is defined in Table 1. Figure 5 shows the manifold during a test.

Table 1. Manifold size

	Real scale	Model scale
Height (m)	3.61	0.103
Width (m)	5.89	0.168
Length (m)	11.51	0.329
Mass (Kg)	100000	2.332

The steel cable used in the experiments has the equivalent stiffness of the original cable (EA=1750MN), in scale of 1:35. For the 100m setup, a 2.86m length of that cable was used, with no additional spring. The small-scale stiffness of the cable was verified by means of a static test, resulting in 15.64Kgf/cm (1.8 10^4 kN/m in real scale).

To emulate a cable with 800m, due to the limited depth of the tank, the same cable length was used and a spring was attached to it. The final stiffness, for the entire setup (cable+spring), was 1.70kgf/cm (2.0 10^3 kN/m in real scale).

Since the manifold presents sharp edges and well-defined separation points, the Reynolds dependence is expected to be small. The hydrodynamics properties in model scale should be similar to the real scale values.

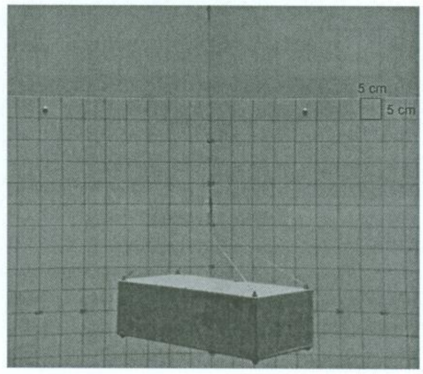


Figure 5. Manifold model connected with the cable and grid to visualize the movements.

Conventional launching test

As mentioned above, two different setups were considered. The conventional launching setup was used to verify the manifold damping coefficient and to compare the dynamic response with the Y-launching setup. Figure 6 presents the conventional launching setup, attached to the wave basin bridge carriage. A square grid was used behind the manifold model to quantitative visualization of the movements. (Figure 5 and Figure 7).

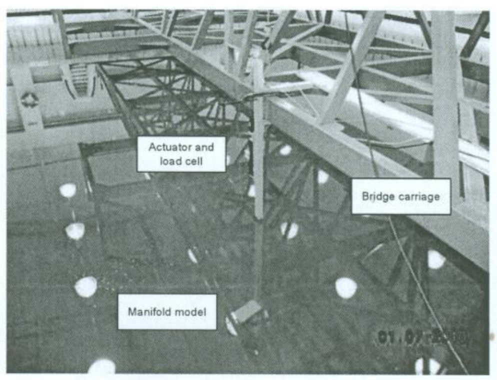


Figure 6. Conventional launcher experimental setup.

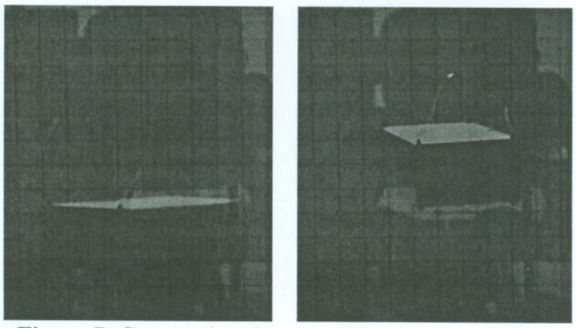


Figure 7. Conventional setup – The extremes of the movement.

Y-launching test

Figure 8 presents the Y-launching setup attached to the bridge carriage. In that test, two actuators and two load cells were used. The cables dimensions were defined according to Figure 9, considering only the 100m depth case. The two cables were connected to the actuators and the smaller cable was connected to the manifold model.

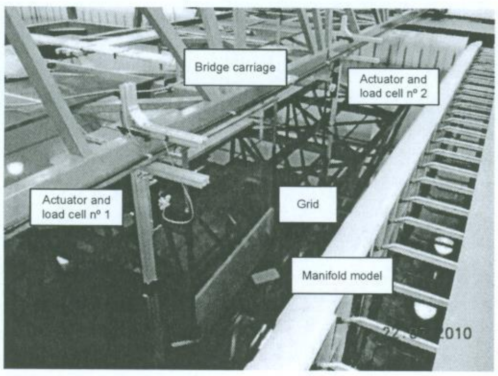


Figure 8. Y type launcher experimental setup.

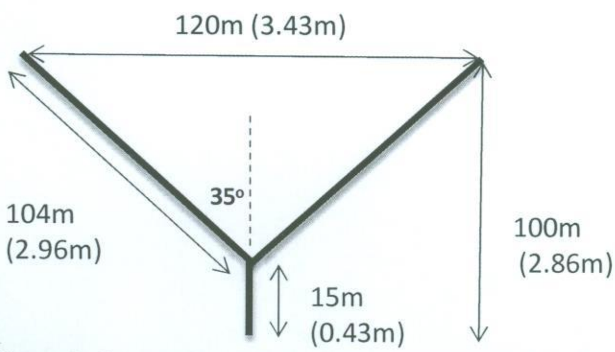


Figure 9. Geometric cable arrangement of Y type launcher. Dimensions indicated between parentheses are in the scale used in the experiments (1:35).

RESULTS AND DISCUSSION

Conventional launching test

Table 2 presents the experimental conditions used to evaluate the load for 100m and 800m cable length, considering one period (8s) and several amplitudes of induced motion. All results and values are presented in real scale. This period was defined since it is the average peak period of the primary wave in Campos Basin. A more complete analysis concerning different wave periods shall be conducted using numerical simulation, as described in the companion paper (Rateiro et al., 2011).

Table 2. Conventional launching test experiments.

Cable length (m)	K_{teo} (KN/m)	K_{exp} (KN/m)	T (s)	Amplitudes (m)
100	17500	18795	8	0.35 0.54 0.70 0.84 0.98 1.05 1.26
800	2187.5	2042.9	8	0.35 0.54 0.70 0.84 0.98 1.05 1.26 1.33 1.40

The following figures shows some illustrative results of the tension in the cable:

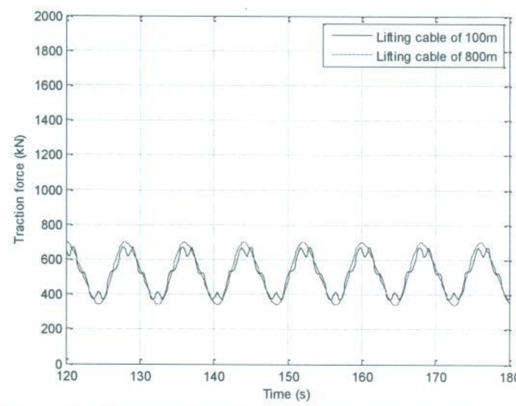


Figure 10. Conventional launching - period of 8s and amplitude of 0.35m.

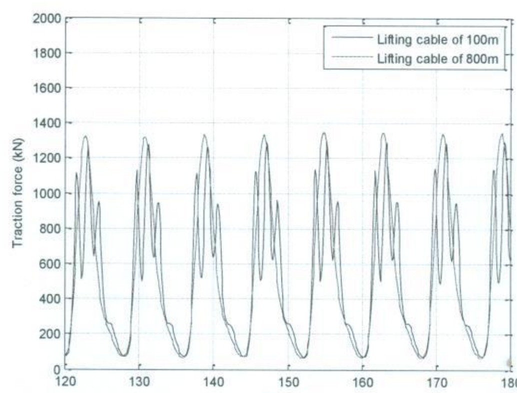


Figure 11. Conventional launching - period of 8s and amplitude of 1.05m.

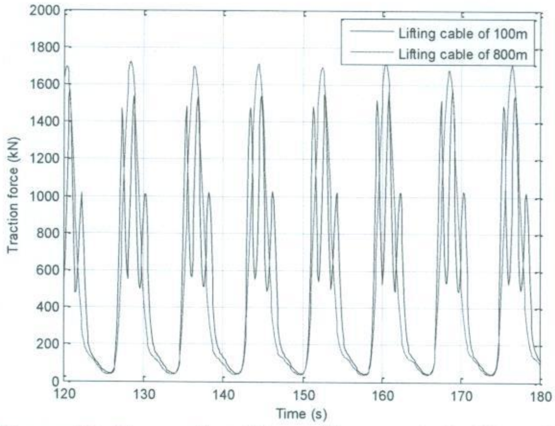


Figure 12. Conventional launching - period of 8s and amplitude of 1.26m.

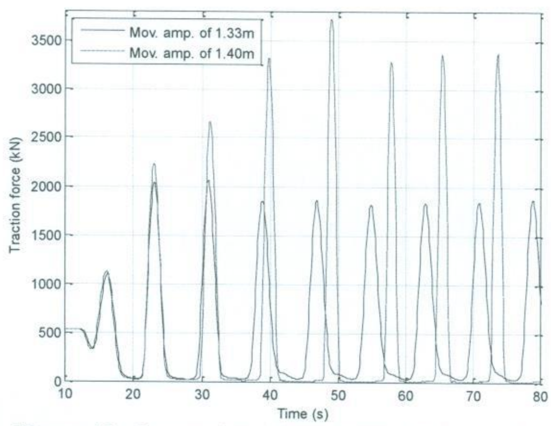


Figure 13. Conventional launching – 800m cable. Comparison between the two larger amplitudes.

For the cable of 100m (larger stiffness), a high frequency component is present. This effect is caused by the angular oscillation induced in the manifold after the cable slackening. The same behavior is not verified in the case of the cable with lower stiffness (800m), since this angular motion is somewhat reduced by the larger complacence of the cable.

For amplitudes larger than 1.05m, the minimum tension approaches to zero, and the slackening is responsible for a sudden increase in the traction. This effect is more evident in Figure 13.

The slackening is caused by a fast induced uplift motion in the manifold (Figure 14). After that, due the drag, the descending motion is slower than the cable tip descending motion, and the cable gets then slackened. When the exciting motion reverses, the large inertia (proper mass and added mass) of the manifold (that is still descending), causes a large peak in the cable traction.

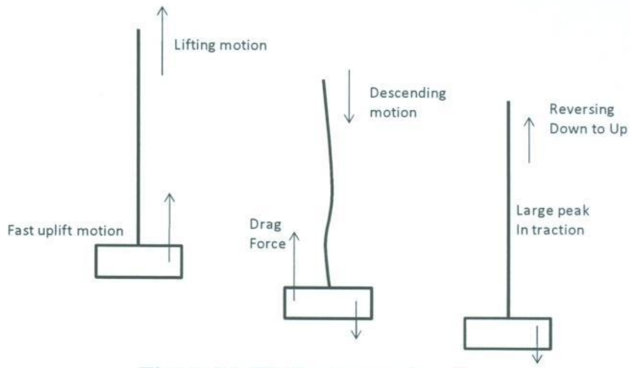


Figure 14. Slackening explanation

Figure 15 and Figure 16 presents the summary of all tests for the conventional launching. The maximum and minimum forces were calculated using the average of the peaks values of a interval of time with stable behavior. Again, it is possible to verify the cable slackening for amplitudes larger than about 1 m.

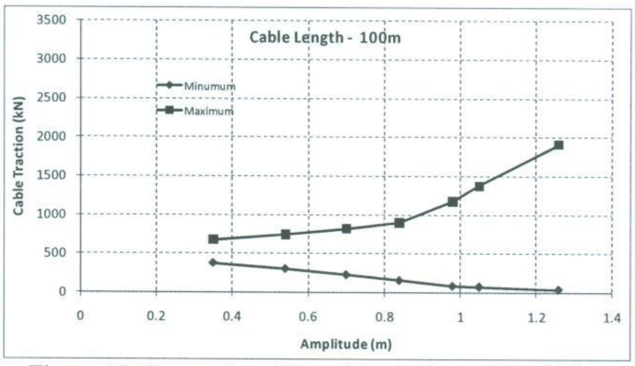


Figure 15. Conventional launching tests results – 100m cable.

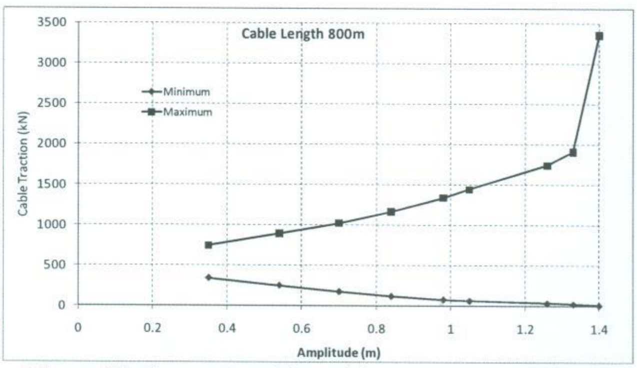


Figure 16. Conventional launching tests results – 800m cable.

Y-launching test

Y-launching was tested considering the 100 meters depth and sinusoidal exciting motions with 8s period. The main objective was to verify the dynamic response with different phase shift between vessels motions, and to demonstrate that there is a reduction in the forces if the vessels are moving in opposite phases. For each phase shift, several amplitudes were considered. Table 3 presents the parameters of the tests.

Table 3. Y-launching test experiments.

Depth (m)	Phase shift (degree)	Amplitudes (m)
100	0	0.35 0.54 0.70 0.84 0.98 1.05 1.26 1.33 1.40 1.50 1.65 1.85
100	30	0.35 0.84 1.05 1.33 1.50 1.85
100	60	0.35 0.84 1.05 1.33 1.50 1.85
100	90	0.35 0.84 1.05 1.33 1.50 1.85
100	120	0.35 0.84 1.05 1.33 1.50 1.85
100	150	0.35 0.84 1.05 1.33 1.50 1.85
100	180	0.35 0.54 0.70 0.84 0.98 1.05 1.26 1.33 1.40 1.50 1.65 1.85

Figure 17, Figure 18 and Figure 19 show results for three different amplitudes. The traction in only one cable is presented, since the traction at the second cable has the same amplitude with a different phase shift. Each figure contains the result for excitation in the same phase (0°), 60°, 120° and 180° phase shift (the latter corresponds to an opposite motion excitation).

For a small excitation amplitude (0.35m, Figure 17), the traction is oscillating around the mean static values, for any phase shift, without cable slackening. However, for larger amplitudes (1.33m and 1.85m), it can be verified that cable slackening and abrupt peaks occur for phase shifts of 0° or 60°.

Figure 20 illustrates the induced movement in the manifold, for exciting motions at the same or in opposite phases. In the first case, only vertical motion is induced in the manifold, and the same behavior of the conventional launching is verified. In this case, slackening occurs. For the second case, the geometry of the cables induces a lateral displacement of the manifold, instead of a pure vertical motion, reducing the occurrence of cable slackening.

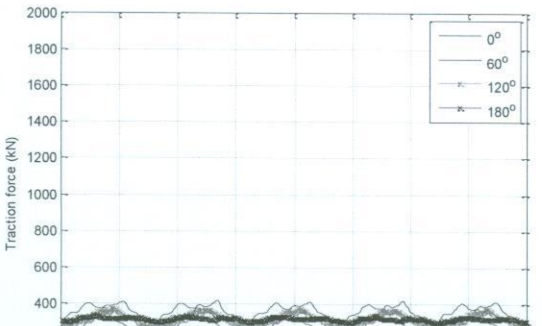


Figure 17. Y-launching – 0.35m amplitude.

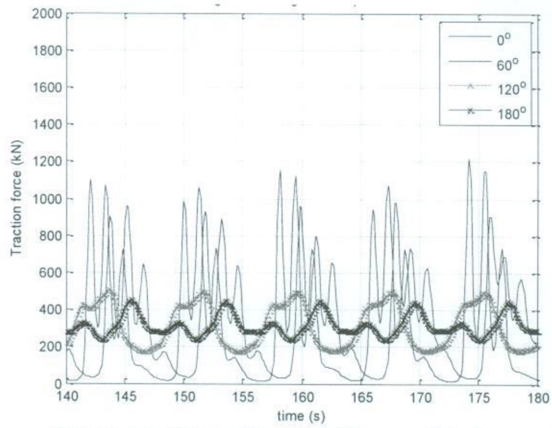


Figure 18. Y-launching – 1.33m amplitude.

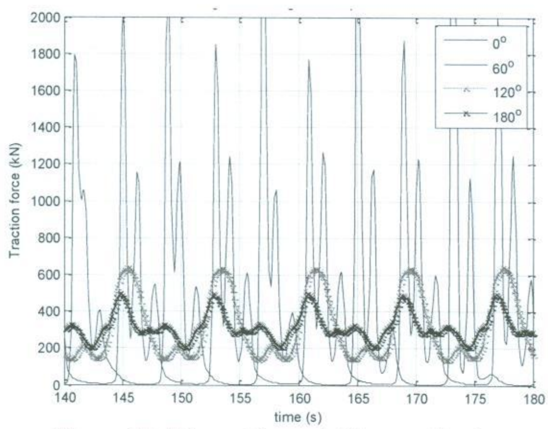


Figure 19. Y-launching – 1.85m amplitude.

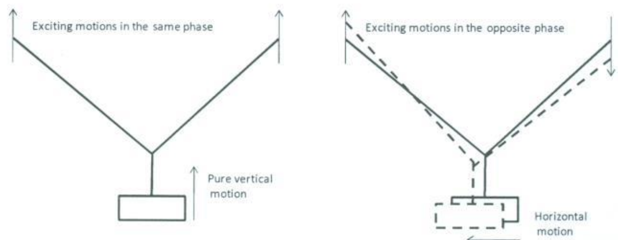


Figure 20. Y-launching – Difference of motion due to the phase shift.

The summary of the results from Y-launching experiments are presented in the next figures (Figure 21 to Figure 24). The reduction of cable traction with increasing of the phase shift gets evident from the observation of those figures.

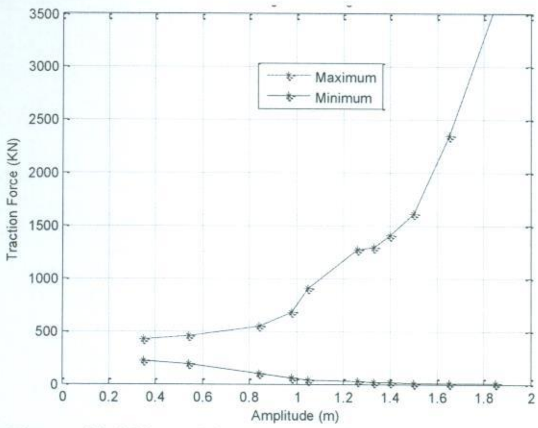


Figure 21. Y-launching - summary - 0° phase shift.

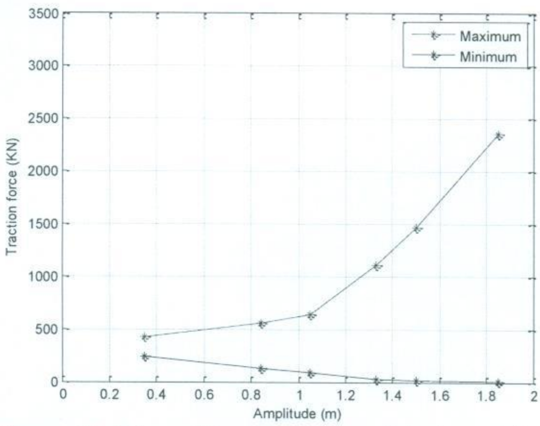


Figure 22. Y-launching - summary - 60° phase shift.

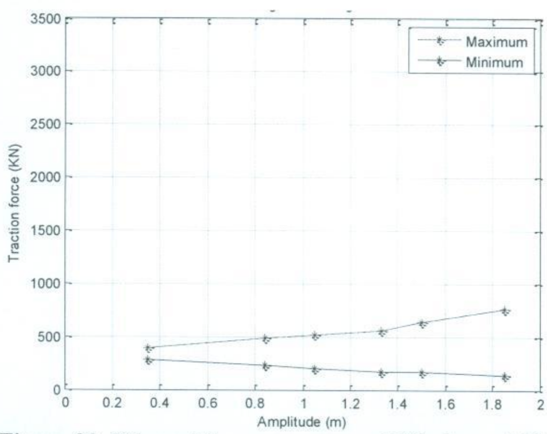


Figure 23. Y-launching - summary - 120° phase shift.

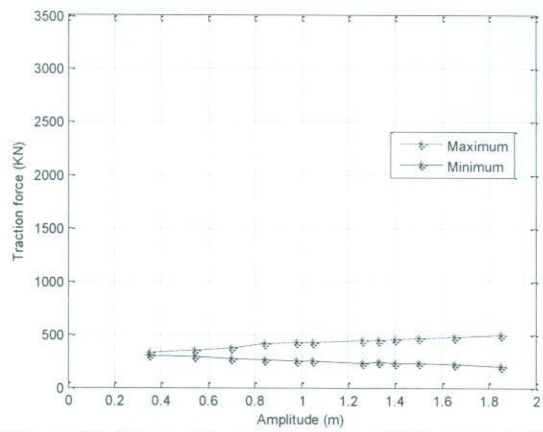


Figure 24. Y-launching - summary - 180° phase shift.

MATHEMATHICAL MODELING

Simplified models of the dynamics involved at the tests were proposed, in order to adjust the damping coefficient acting on the manifold. This parameter is important for a comprehensive numerical analysis, presented in the companion paper (Rateiro et al., 2011).

Conventional launching model

Figure 25 presents the 1 degree of freedom model proposed for the dynamic of the conventional launching procedure. It considers a mass-spring oscillator with linear damping in a vertical direction (heave) and linear cable stiffness with no compression.

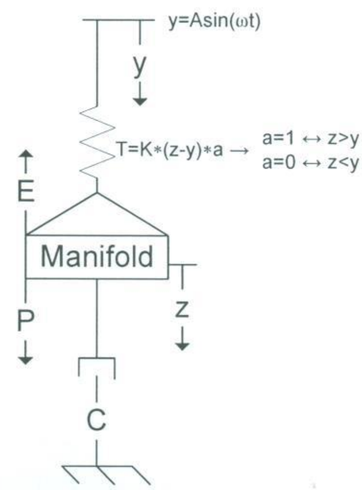


Figure 25. Conventional launching - simplified dynamic model

The second order dynamic response in heave is then given by:

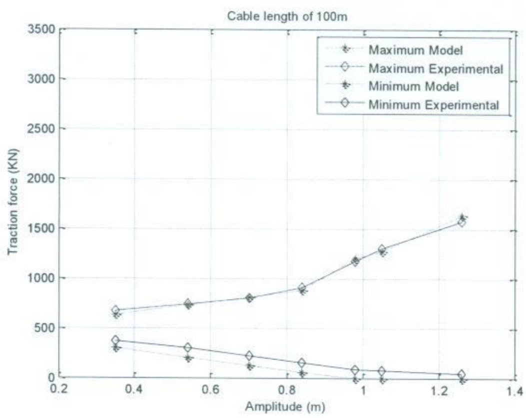
$$(M + M_z)\ddot{z} + C_z\dot{z} + T = P - E \quad (1)$$

where:

M - Manifold proper mass ($1 \times 10^5 kg$)

M_z - Vertical hydrodynamic added mass ($3.5 \times 10^5 kg$)
C_z - Vertical linear damping coefficient (*to be adjusted*).
K - cable stiffness ($1.8 \times 10^7 N/m$ for 100m and $2.0 \times 10^6 N/m$ for 800m depth)
T - Cable traction force (described in Figure 25).
P - Manifold weight ($9.8 \times 10^5 N$)
E - Manifold buoyancy ($5.0 \times 10^5 N$)
z - absolute vertical position of the manifold
y - absolute vertical position of the top of the cable (exciting motion)

Vertical damping coefficient was adjusted in order to match the forces predicted by the mathematical model and those obtained in the experiments. The value of damping coefficient that better fits the experimental and numerical results is 5.0×10^5N.s/m. Figure 26 presents the comparison between numerical model and experimental results. A very good agreement can be observed for both cable lengths. The differences in the minimum traction may be explained by the behavior of the load cell when the forces reduces to almost zero. There is a dynamics (due to electrical and mechanical properties of the load cell) that is not considered in the mathematical model.



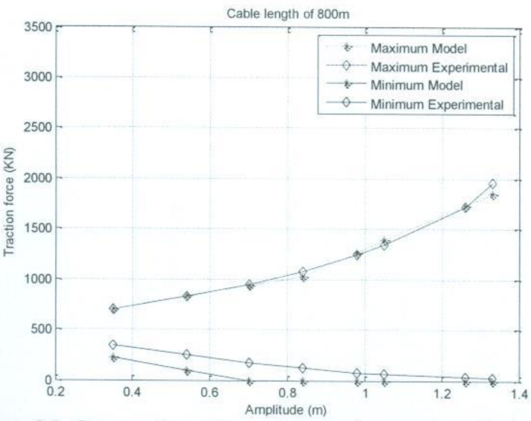


Figure 26. Conventional launching - Comparison between experimental and numerical model results.

Y-launching Model

In order to simulate the behavior of the Y-launching experiments, a 2 degrees of freedom model was proposed, show in Figure 27.

The mathematical model for the two directions can be written as:

$$\begin{aligned} (M + M_z)\ddot{z} + C_z\dot{z} + T_{1v} + T_{2v} &= P - E \\ (M + M_x)\ddot{x} + C_x\dot{x} + T_{1h} + T_{2h} &= 0 \end{aligned} \quad (2)$$

where:
T_{iv} - Vertical projection of the cable i traction force (i=*1;2*)
T_{ih} - Horizontal projection of the cable i traction force (i=*1;2*)
M_x- Horizontal hydrodynamic added mass ($0.5 \times 10^5 kg$)
C_x- Horizontal linear damping coefficient (1.5×10^5N.s/m)

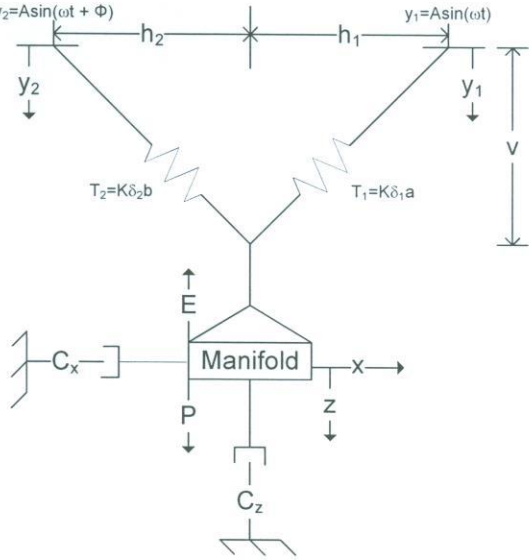


Figure 27. Y-launching - simplified dynamic model.

The traction forces can be written as:

$$T_{iv} = k_i\delta_i \frac{v}{\sqrt{v^2 + {h_i}^2}} a_i \qquad T_{ih} = k_i\delta_i \frac{h_i}{\sqrt{v^2 + {h_i}^2}} a_i \quad (3)$$

being L_i the cable length at the equilibrium and

$$a_i = 1 \text{ if } \delta_i > 0 \text{ and } a_i = 0 \text{ if } \delta_i < 0 \quad (4)$$

$$\delta_i = \sqrt{(v + z - y_i)^2 + (h_i + x)^2} - L_i \quad (5)$$

Considering the same vertical damping coefficient adjusted by the conventional launching tests, Figure 28 to Figure **31** present the comparison between numerical model and experimental results. A very good agreement can be observed for almost all cases, except those with a very large peak forces.

The high frequency components observed in the experiments (see Figure 19 for example) are not included in the simplified dynamic model, since they are related to angular motion of the manifold.

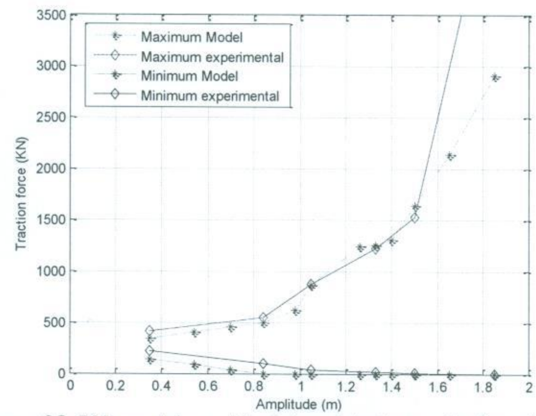


Figure 28. Y-launching - Model and tests results for phase shift of 0°.

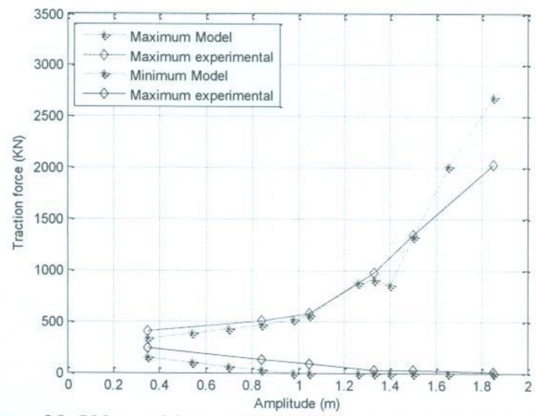


Figure 29. Y-launching - Model and tests results for phase shift of 60°.

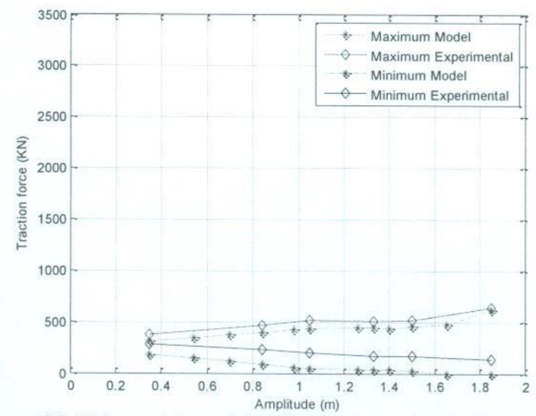


Figure 30. Y-launching - Model and tests results for phase shift of 120°.

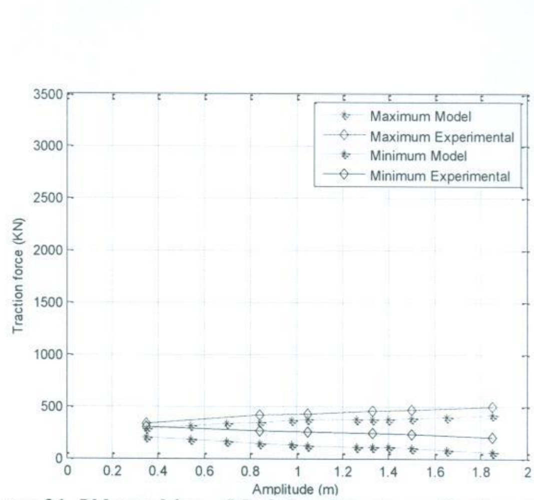


Figure 31. Y-launching - Model and tests results for phase shift of 180°.

CONCLUSIONS

This work is the first part of an illustrative case of the joint application of simplified experimental tests and numerical simulations for the proper analysis of a complex offshore operation (launching of a subsea equipment using one or two vessels).

The hydrodynamic properties of the subsea equipment could be calculated, using a simplified mathematical model. Important conclusions about system dynamics (cable slackening) could also be drawn. The model describe the behavior of the system with good agreement with the experimental results. The mathematical model is now a good tool for future studies and for hybrid (numerical and experimental) analyses.

The reduction of the cable load proposed by the Y type launcher was verified. The phase shift between the motion of vessels reduces considerably the cable traction and the occurrence of slackening, when compared to the conventional launching method (one vessel operation).

In the companion paper (Rateiro et al., 2011), numerical simulations were conducted, considering the coupled dynamics of the vessels, cables and equipments under irregular sea state. Those simulations are used for determining the limiting environmental condition for a safe operation and to propose a vessel positioning strategy for the whole launching operation.

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