INVESTIGATIONS ON TORPEDO ANCHOR BEHAVIOR DURING LAUNCHING

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Abstract: The torpedo anchor is a pile device developed to hold floating offshore systems in a range encompassing from small buoys (250 tons of displacement) to very large production platforms (300000 tons). One of its advantages is that it can be easily installed just by launching it vertically. In fact, the name torpedo came from this installation characteristic. It was applied for the first time in 1997 with mooring power ranging from 140 to 900 ton, and with cost up to three times lower (or more) than other conventional mooring systems.
This work presents a study about the torpedo anchor launching. Comparisons were performed between a numerical analysis, reduced model tests and, most importantly, full scale results.
The numerical simulations include variations on the hydrodynamic properties of both the torpedo anchor and the mooring lines. The study was complemented with tests to get the drag, the lift and the moment as a function of the relative flow angle of incidence.

Keywords: Torpedo Anchor, Anchoring systems, Slender body drag and lift,

NOMENCLATURE

V_T	terminal velocity
F_D	drag force
r	water density
g	gravity acceleration
D_{ef}	effective axial diameter
$pD_{ef}\,\mathbf{l}$	wetted area
∇	volume
A_T	frontal area
m	mass
m	mass per length unit
$\mathbf{l}$	length

1- INTRODUTION

The offshore industry was born in the Gulf of Mexico in the fifties and its development was driven by higher oil prices in the seventies. Particularly in Brazil, the oil production has been made in very deeper waters (2000 m). These practices have led to an evolution of the mooring systems and also anchoring systems. Some new ones were never tried before. In this category one may include the development of polyester cables which were lighter and as strong as steel. Another of such a kind of new development comes from the need to decrease the anchoring radius: they are the VLAs (Vertical Load Anchoring) which as the name says resists to the vertical load besides the horizontal ones. For example, the radius of a taut leg anchorage system using polyester mooring and VLAs is two to three times smaller than the radius of a equivalent catenary anchor system.

Within this picture there are the torpedo anchors, a new kind of VLA. The development has been made by PETROBRAS since 1996. Its holding power is from 140 to 900 tons and with a cost 30% when compared with conventional system. This includes material and installation expenses.

The installation of the torpedo anchor is the objective of the present paper. This is done by a combination of numerical analysis and full-scale measurements what is done by the first time. The present work is first developed by Falcão [1].

2 – THE INSTALLATION OF TORPEDO ANCHOR

The installation of the torpedo anchor is done usually with two vessels. The auxiliary vessel where is the anchor, allows the adjustment of the vertical position of the torpedo anchor by lifting it to the point of release. The second vessel launches the set by releasing the auxiliary mooring. Subsequently the torpedo and the principal mooring line (the one the will be connected to the platform) are released together. Figure 1 shows the initial configuration just before the release. Figure 2 follows with more details and definitions.

It is important to say that usually a first torpedo (the test torpedo) is released to define the best configuration of the arrangement of lines and the best initial position above the sea bottom. In any torpedo anchor is instrumented with accelerometers. This allows the measurements of the time series of six variables: three displacements and three rotations. A pressure cell is used get the incila vertical position. The data are used to prepare a standard final report which includes the maximum and terminal speed, the depth and the angle of penetration of the anchor. With these data, the anchor may be approved or not. If disapproved, the torpedo is recovered in up to 7 days while the holding power is small before the soil set down.

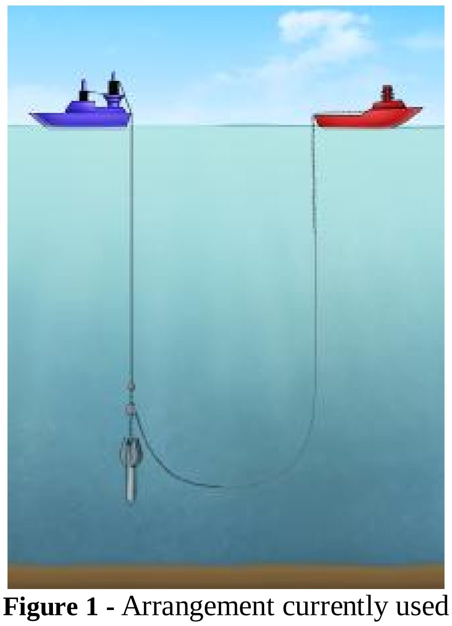

Figure 1 - Arrangement currently used

In order to set a numerical background for the installation analysis the study used the configuration mentioned above. Then numerical simulations using a non-linear time domain computer program [2] were done varying the hydrodynamic properties of the torpedo anchor and the structural properties of the anchorage lines. Table 1 defines the mooring lines properties. Table 2 defines the parametric variation.

Table 1. Properties of the Mooring Line

MORRING		
Diameter	m	0,120
O D	m	0,216
I D		0
Mass / Length	te/m	0,28656
Axial stiffness	kN	1229760
Bend stiffness		0
Limit Compression		yes
Normal drag coefficient		1,0
Normal drag diameter		0,252
Axial drag coefficient		0,4
Axial drag diameter		0,0229
Normal added mass coefficient		1,0
Axial added mass coefficient		0,08

LINES						
		Segment 1	Segment 2	Segment 3	Segment 4	Segment 5
Material		Still Cable	mooring	Poliester	mooring	mooring
Nominal Diameter	m	0,0250	0,1030	0,1250	0,1030	0,1030
Diameter	m	0,0500	0,1854	0,1250	0,1854	0,1854
Length - conf 35 t	m	410	50	430	60	50
Length - conf 98 t	m	970	100	970	120	50
Mass per Length	t/m	0,0970	0,2110	0,0120	0,2110	0,2110
Axial drag coefficient		0,0017	0,0400	0,0017	0,0400	0,0400
Normal drag coefficient		1,2000	1,0000	1,2000	1,0000	1,0000

Table 2. Parametric variations

TORPEDEOS			
Mass	t	35	98
Diameter	m	0,700	1,067
Length	m	13,50	17
Axial drag area	m^2	0,505	1,074
Axial drag coefficient		0,340	0,34
Normal drag area	m^2	16,862	33,032
Normal drag coefficient		1,255	1,267

The hydrodynamic coefficients of the torpedo and of the anchorage lines were estimated from data and procedures available and suggested in the literature [3], [4]. Besides, to complement the study, tests with a model in scale were performed in the currents channel of LOC - Laboratory of Waves and Currents of COPPE / UFRJ. The objective of the tests was to determine the behavior of the drag and normal forces depending on the angle of attack of the flow as well as to confirm the estimated coefficients from the available literature [3], [4].

3 - METHODOLOGY

As mentioned in the previous section, the work consists in numerical simulations with the aid of small-scale experiments for obtaining the hydrodynamic coefficients of the torpedo. Figure 2 shows a layout with the simulated configuration.

The configuration consists in five segments of lines as shown on the right of Figure 2. The first one on the top connects to first launch vessel and it is made of steel wire. The second, third and fourth segments form an anchorage set that will be connected in the top to the vessel two (the recovery or anchorage vessel). The second and fourth segments are made of mooring lines and have approximately 50 meters in length. The fourth segment is made of a polyester rope. The fifth segment is made of mooring line and is also part of the anchor line after the installation. The meeting point between the segments is a delta-plate connection.

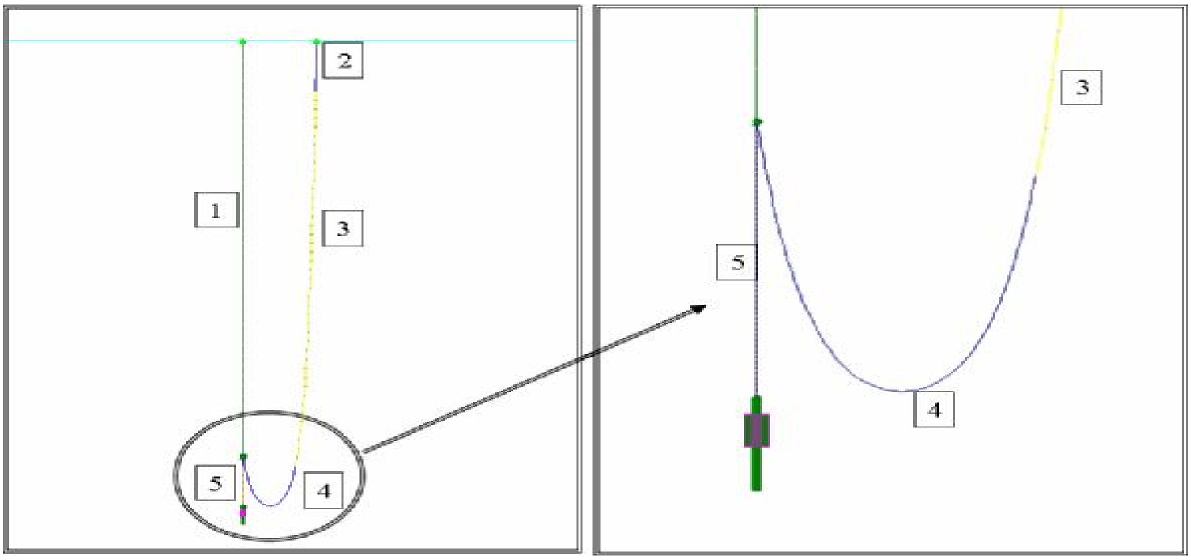

Figure 2 – Configuration simulated in the program [2]; 1: installation cable, 2: launching cable, 3, polyester cable, 4, recovering cable and 5 auxiliary mooring. On the right a zoom form the circle on the left.

Among the structural parameters, it is necessary to get the mass and moments of inertia of the torpedo and bending and axial stiffness of the three types of lines. These properties can be easily found using the information of manufacturers [4]. The only matter of research arises from the determination of the adequate hydrodynamic coefficients of torpedo for the actual case under consideration. There are not so many information on this subject in the open literature. This is so probably because the anchor lines are designed with static properties.

4. HYDRODYNAMIC COEFFICIENTS

The results presented in scale in Figures 3 and 4 aim to provide a consolidation of the hydrodynamic coefficients of drag and normal force.

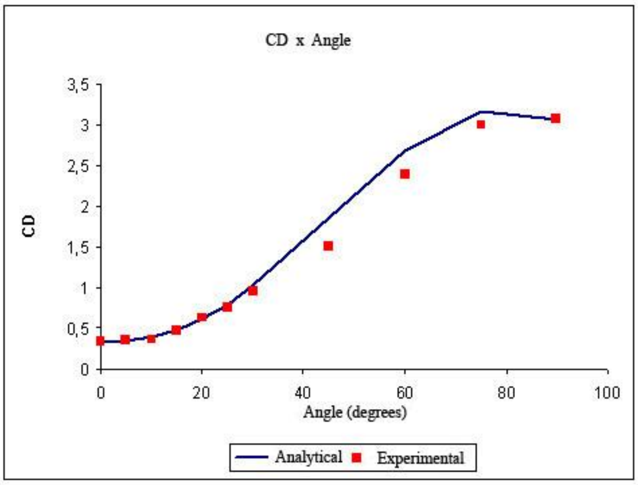

Figure 3 - Drag coefficient x angle of attack

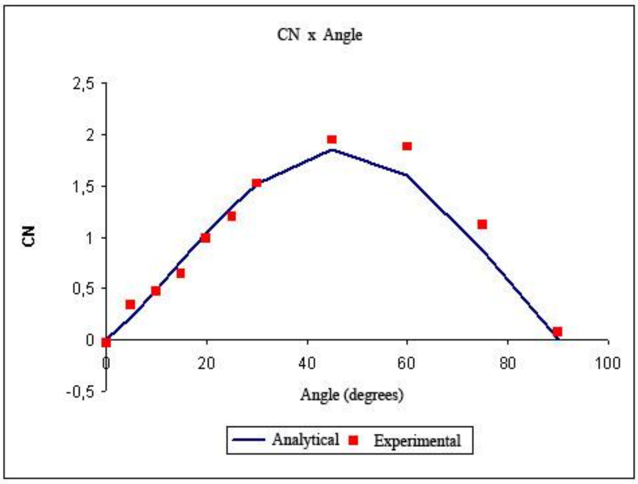

Figure 4 - Coefficient normal force x angle of attack

The experiments in Current Channel in the LOC, the average speed was taken to be 0.63 m/s. The scale of the torpedo anchor model was 1:30. The experimental results are given in Figure 3 and 4. In these figures a comparison with empirical formulation are also shown but the last ones are out of the present scope. They will be discussed in future works. The value obtained experimentally was C_D = 0.34, which confirmed the proposition in [3]. Here the force coefficient was made non-dimensional by the frontal area.

5. TIME DOMAIN SIMULATIONS

It is know that terminal velocity of the torpedo anchor is defined by the velocity reached after the acceleration becomes null due the balancing between the drag and gravity efforts. To get this terminal velocity and the time until the sea floor is hit, several simulations were conducted and compared with full scale measurements.

The simulations were performed for two torpedoes: 35 tons and 98 tons. The dimensions of the torpedo and the lines and the theoretical coefficients calculated and the general parameters considered for simulation are presented in Table 2.

The coefficient of normal force as mentioned was calculated from the balance between available values for cylinders and plates. The value of this coefficient calculated for each torpedo is near the value obtained experimentally for an angle of attack equal to 30 degrees.

Figures 6 and 7 present the results of simulation for the two torpedoes in terms of speed of falling over time. There were variations in the value of the coefficient of axial drag. Variations were $C_D = 0$ for both, in order to get an idea of the influence of number of lines in the fall of the torpedo, $C_D = 0.22$ and $C_D = 0.18$ for the torpedoes of 35 and 98 tons; $C_D = 0.34$ for both experimentally obtained and $C_D = 0.5$ for both for simple research. The results are shown in Figure 5.

The best results were achieved with CD = 0.34 as shown in Figure 15 along with data from the actual scale. In Figure 16 are shown the measurement of releases for the torpedo of 35 tons (Bar 10-09 and 11-09) made in Barracuda's field [12] and for the torpedo of 98 tons (P 21-04) conducted in the Marlin Leste's Field (Petrobras 53 platform) [12].

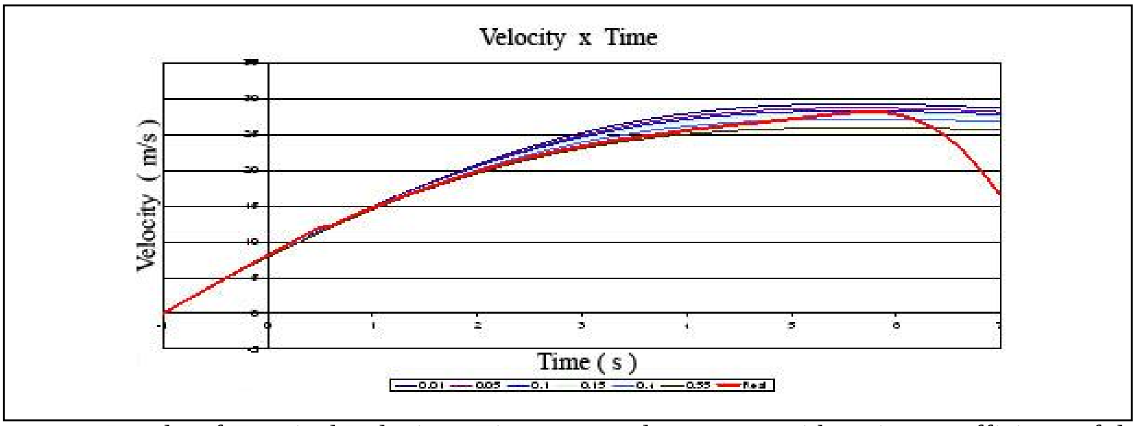

Figure 5 - Results of Terminal Velocity x Time to torpedo compare with various coefficients of drag

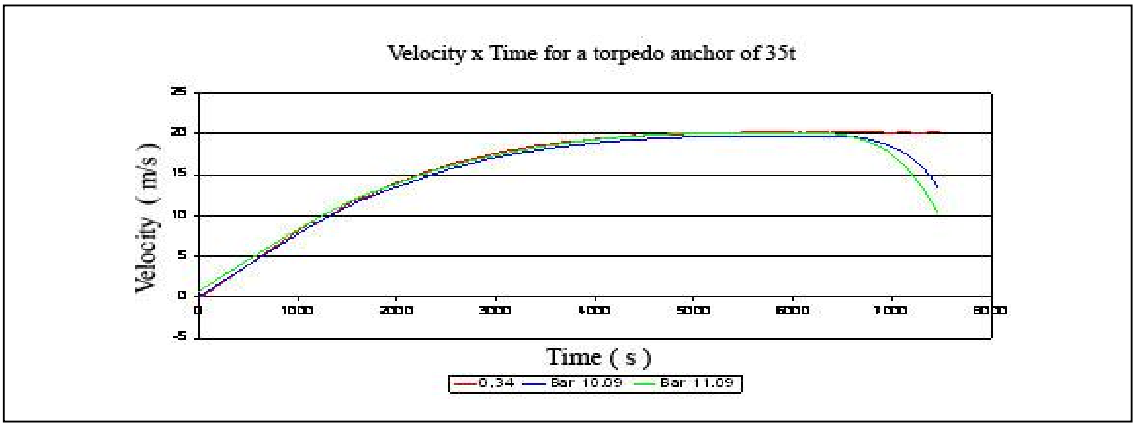

Figure 6 - Results of Terminal Velocity x Time for the torpedo to 35 tonnes, is comparing the predictions of the numerical code with CD = 0.34 (the vertical line 50m) and two measurements of actual entries in the Barracuda field on September, 10-11, 2008

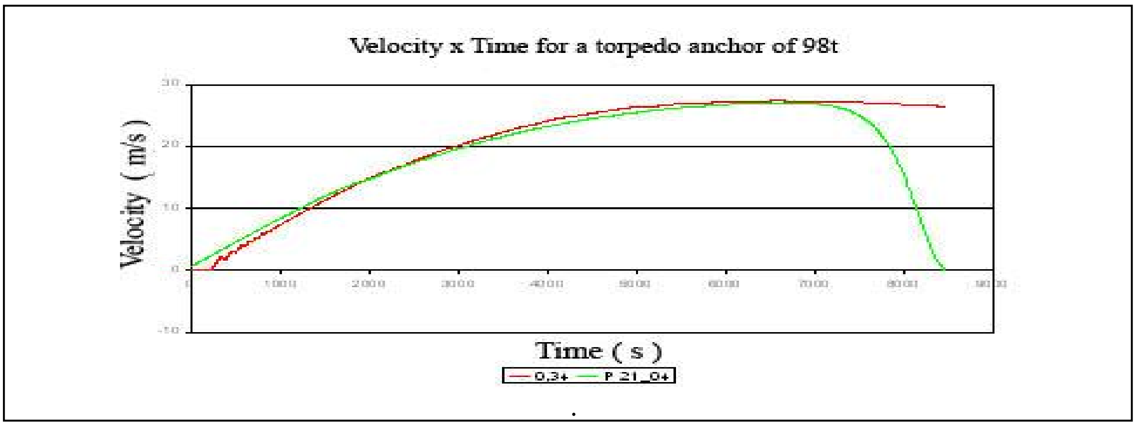

Figure 7 - Results of Terminal Velocity x Time to torpedo of 98 tonnes, is comparing the predictions of the numerical code with CD = 0.34 (the vertical line 50m) and two measuring scale in the of real launch in Marlim Leste field on April, 21, 2008.

Cases with only rags of tethers falling vertically are analyzed further. The lengths of the rags are 100, 250 and 500 meters and the results are shown in Figure 8. The objective is to evaluate the drag due to friction in the mooring and its consequences in the terminal velocity.

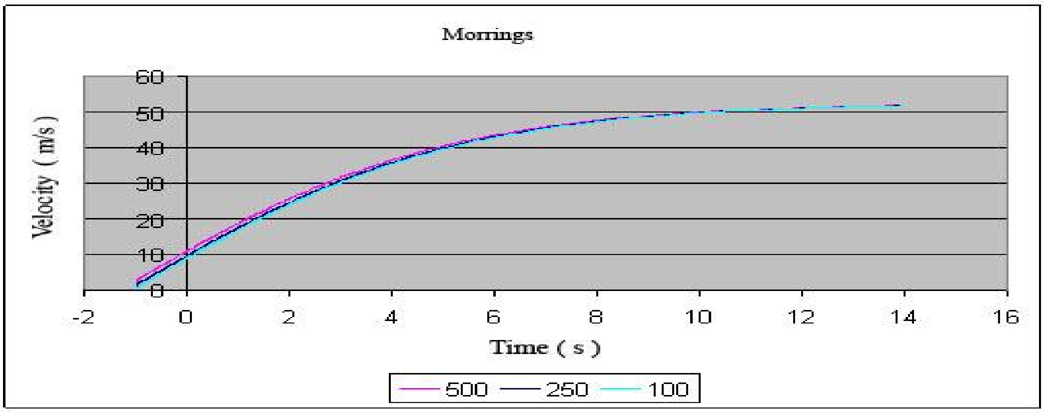

Figure 8 - Result of Terminal Velocity x Time for rags of tethers with 100, 250 and 500 meters vertically launched

The formulation of the numerical code is almost independent of the length of the mooring cable with respect to terminal velocity, the values used in this simulation are in Appendix A.

This can be seen pointing out the equation of the terminal velocity, which as mentioned in Fernandes, 2006[10], it is given by Equation (2).

$$V_T = \sqrt{\frac{(m - \rho\nabla)g}{\frac{1}{2}\rho C_D A_F}} \qquad (2)$$

The expression for the force of drag in [1] is:

$$F_D = \frac{1}{2} r p D_{ef} \mathbf{l} C_D V|V| \qquad (3)$$

At the same time, for a vertical mooring:

$$m = m\mathbf{l} \qquad (4)$$

$$\nabla = A_T \mathbf{l} \qquad (5)$$

$$C_D = C_{Dz}$$ ie drag in longitudinal direction

Furthermore:

Considering (3), (4) and (5) the total length of the morring is canceled by the expression of the terminal velocity of the vertical as shown in Equation (6)

$$V_T\Big|_{amarra} = \sqrt{\frac{\left(m - \Delta_T\right)g}{\frac{1}{2}rpDC_{Dz}}} \tag{6}$$

This is a kind of paradox (paradox of morring) which says that the terminal velocity of the morring do not depends on their length.

Furthermore, we find that the case simulated in Figure 8 (with torpedo and a vertical mooring) shows a difference between the two measured launches. However the order of magnitude is the same.

For both launches the variation of drag coefficient of torpedo in the simulation may not have made much difference in the results. Furthermore, Annex A, $C_{Dz} = 0{,}4$ e $D_{ef} = 0{,}023$ what results in insignificant contribution of the moorings. Thus, in comparison with measurements of the actual scale, there is room in search for a more appropriate adjustment of the coefficients of drag (and torpedo lines separately). Remember that the goal here is to assess the size of properties.

6 – FULL SCALE RESULTS

This study was completed with a monitored mission of launching of 8 torpedoes, aboard the Maersk Boulder. The follow-up period was 20 days.

In this service there was a discontinuity in the time series of acceleration. It was reproduced in the numerical simulation. Figures 9 and 10 show both time series respectively.

The occurrence of this discontinuity is been studied in another studies by COPPE / UFRJ.

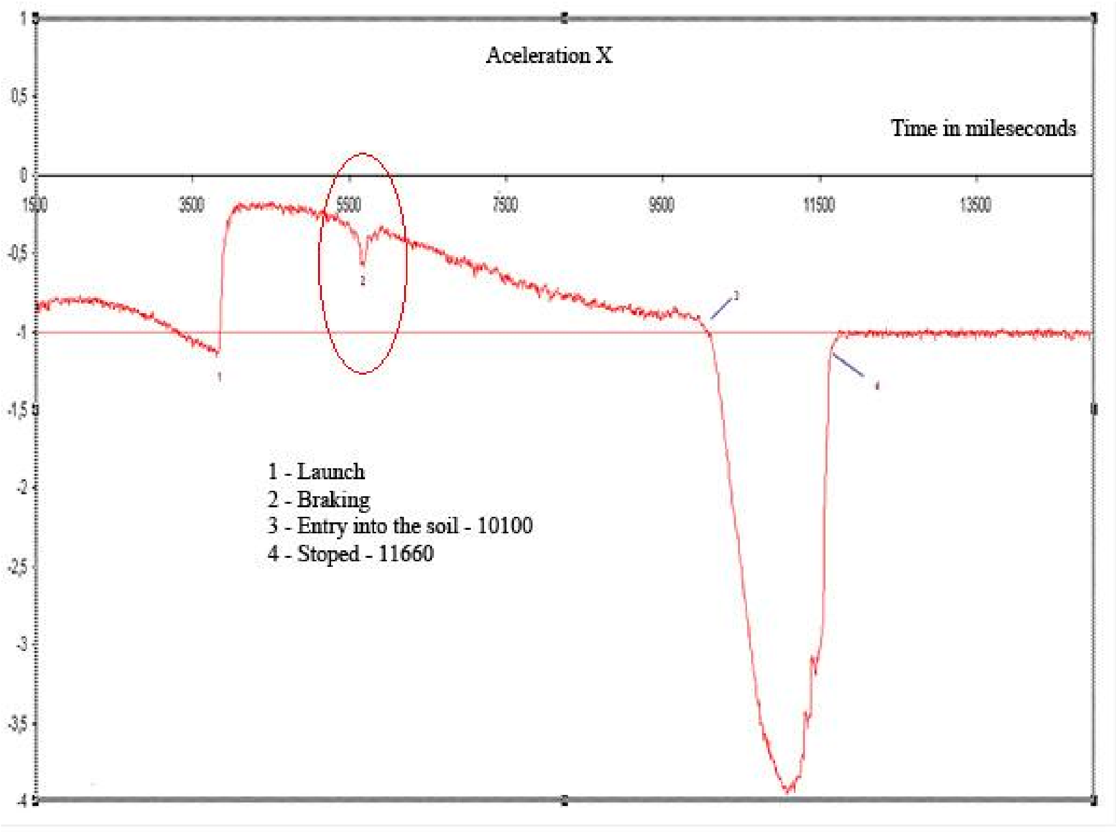

Figura 9 – Acceleration time series of scale obtained by the bottle
(the discontinuity mentioned in detail)

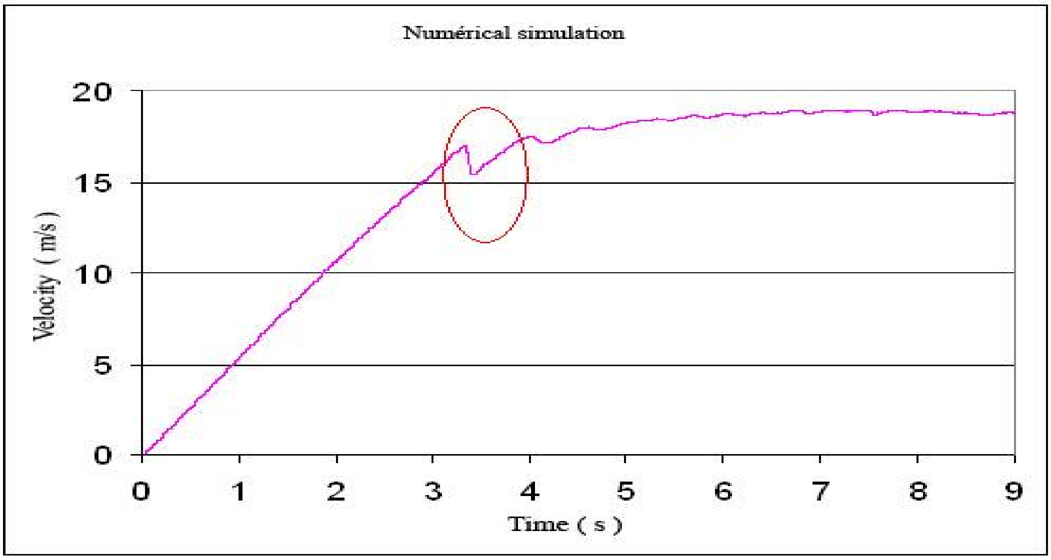

Figura 10 – Acceleration time series of scale obtained by numerical simulation (mentioned in detail the discontinuity)

7 – CONCLUSIONS

The methodology applied for determining the hydrodynamic coefficients with the numerical simulation used to reproduce the dynamic behavior of the system during the launch of the torpedoes proved to be effective in a first analysis. The results (of the code and the actual launches) in terms of terminal velocity were similar. This procedure may be an important aid for the design of new configurations of launch.

The variation of coefficient of drag of the torpedo in simulations is less significant than the drag of the lines for defining the time series of velocity of fall, here are also questions the influence of arrangement of lines.

Once open to the possibility of study shown by this work, it is suggested for future work that a more comprehensive study with results of actual releases and more studies about drag coefficients distribution.

It is suggested that the directional stability should be investigated deeply believing that ensuring the verticality of the trajectory is the key point of studying this type of anchorage. The more vertical, it ensures penetration with a slope closer to zero as possible. This will reduce the waste in launches with great economic results

8 – REFERENCES

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