Wave Induced Loads on the LEANCON Wave Energy Converter

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October 2008

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Preface

This report is a product of the co-operation agreement between Aalborg University and LEANCON (by Kurt Due Rasmussen) on the evaluation and development of the LEANCON wave energy converter (WEC). The work reported here has focused on evaluation of the wave induced loads on the device, based on a desktop study based on available literature, supplemented by laboratory testing of models of the WEC provided by LEANCON.

LEANCON, represented by Kurt Due Rasmussen, has been heavily involved in the testing of the device, including the instrumentation, model setup and execution of the tests in the laboratory, all under the supervision of the personnel of the Wave Energy Research Group at Department of Civil Engineering, Aalborg University.

The report has been prepared by associate professor Peter Frigaard in corporation with assistant professor Jens Peter Kofoed (e-mail: jpk@civil.aau.dk) and research assistant Eliab Ricarte, all from the Wave Energy Research Group at Department of Civil Engineering, Aalborg University.

Aalborg, Oct. 2008

Table of Contents

1 Introduction

The work reported here aims at estimating the wave induced loads on the LEANCON wave energy converter (WEC). Its main purpose is to provide load cases for the FEM analysis and structural design of a prototype planned for deployment in Nissum Bredning, in wave condtions corresponding to 1:10 length scale compared to standard conditions in the Danish sector of the North Sea (Frigaard et al., 2008).

The concept

A detailed description of the concept is given by Kofoed & Frigaard (2008).

Objectives

The work towards the overall objectives of estimation of loads acting on the LEANCON WEC has been divided into describes three main parts, each presented individually in the following.

- Estimation of wave induced loads on the structure in extreme conditions based on available information from literature.
- Measurement of loads on a single pipe model section of the LEANCON WEC in the wave tank. The purpose of this part is to qualitatively investigate the force and moment components of the loading of a single pipe and phase shift between them.
- Measurement of loads on a ten pipe model section of the LEANCON WEC in the wave tank. The purpose of this part is to qualify the values found in the before mentioned desktop study.

The small scale model tests, one single pipe and a ten pipes module, has been tested in the 3-D deep water wave tank at Department of Civil Engineering in Aalborg University. The main results are presented as well the statistical tests performed to validate the procedure. Tests in the tank were conducted in August, 2008.

Two small scale models were submitted to several conditions of work under different regular and irregular waves. The first one is a section with a single pipe where sensors were disposed to read vertical and horizontal force acting on the device.

The second one is a section with ten pipes used to read the moments acting at separated point of the structure of support.

The purpose of those tests is estimate the extreme wave loads on the device and compare the experimental results to that analytical calculated ones from previous Report for validation. Several operational settings were considered as Draught and Valve Setting for example to evaluate its effects on the device. Regression analysis statistical tests were applied to verify correlation between data and to show its validation.

2 Calculation of wave induced loads

Location for load calculations

The load calculations are based on a placement close to the Test Site in Nissum Bredning. The presented results assume a scale 1:10 for LEANCON model at this site.

Figure 1 Nissum Bredning - Location for load calculations

The location is well known by the department from intensively testing of the Wave dragon and Wave Star. Waves have been calculated and measured more or less continuously in the period May 2003 to June 2008. The proposed test location scale North Sea waves approximately 1:10.

The extreme design wave condition is considered to be:

- Hs = 1.0 meter
- Tp = 3.2 sec.
- HHWL = + 1.8 meter

Wave Forces on front

The front of the structure can expect wave pressures from breaking waves. Visual observations from the model testing support that waves will/can break on the front.

Traditionally wave pressures on vertical walls are calculated using Godas Equation (or Godas Extended Equation for irregular waves).

The front of the LEANCON WEC differs from a traditional vertical wall in three ways:

- It is inclined
- It does not go all the way to the bottom. Actually it is cut 0.3 meter below SWL.
- It is permeable. Some water can escape between the cylinders.

Takahashi has given some reduction factors for slit walls (0.3-0.85) and some reduction factors for inclined structures.

The following wave pressures do not take into account these reductions, but are simply calculations of the Goda wave pressures for irregular waves.

Calculated results integrate the pressures from -0.3 meter to 0.9 meter.

Table 1 Max Wave Forces on front of Wave Device

Crest	Draught	Water depth	Hs	Ts	Force	Pmax
meter	*meter*	*meter*	*meter*	*sec*	*kN/meter*	*Pascal*
0.9	0.3	4.0	1.0	3.5	12.9	$12.0 \cdot 10^3$
0.9	0.3	5.0	1.0	3.5	12.4	$11.5 \cdot 10^3$
0.9	0.3	6.0	1.0	3.5	12.3	$11.3 \cdot 10^3$
0.9	0.3	4.0	0.8	3.2	10.4	$9.3 \cdot 10^3$
0.9	0.3	5.0	0.8	3.2	10.2	$9.0 \cdot 10^3$
0.9	0.3	6.0	0.8	3.2	10.2	$8.9 \cdot 10^3$
0.9	0.3	4.0	0.8	3.0	10.0	$8.9 \cdot 10^3$
0.9	0.3	5.0	0.8	3.8	11.2	$9.5 \cdot 10^3$
0.9	0.3	6.0	1.2	3.8	16.8	$14.2 \cdot 10^3$

In the following calculations it is decided to use a maximum force equal to 15 kN/meter and a maximum wave pressure equal to $13 \cdot 10^3$ Pa.

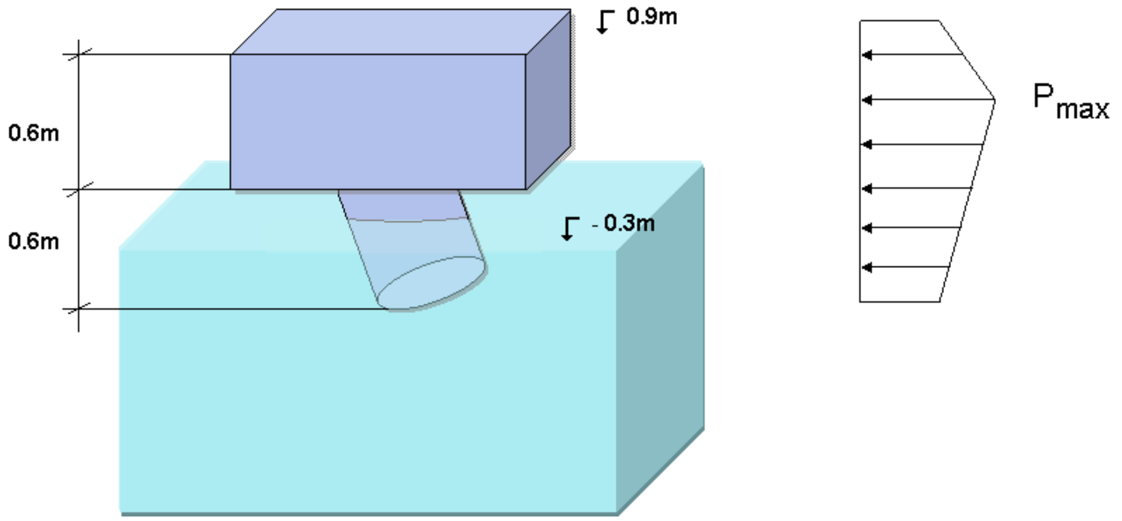

Figure 2 Single Pipe LEANCON and Forces Diagram

Load Case 1

Local impact on tube.

$$F = \text{Load coeff} * P_{max} * \text{Area}.$$

$$F_{impact} = 5.2 * 13 \cdot 10^3 * 0.25 \text{ m}^2 = 16.9 \text{ kN}$$

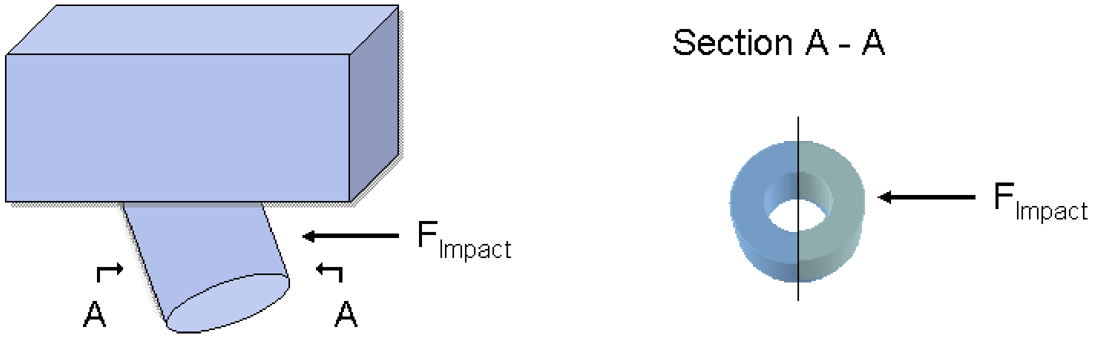

Figure 3 Impact load on tube.

Load Case 2

Bending moment of tube.

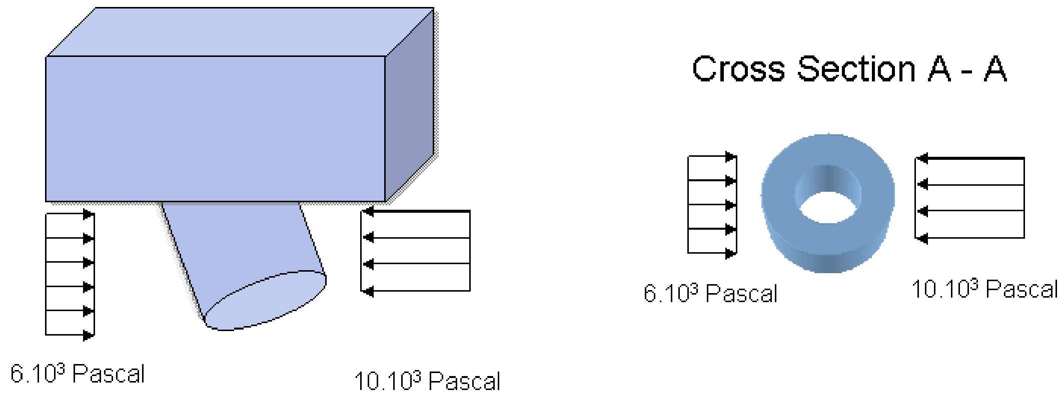

Figure 4 Load on tube.

Load Case 3

Main Beam Bending.

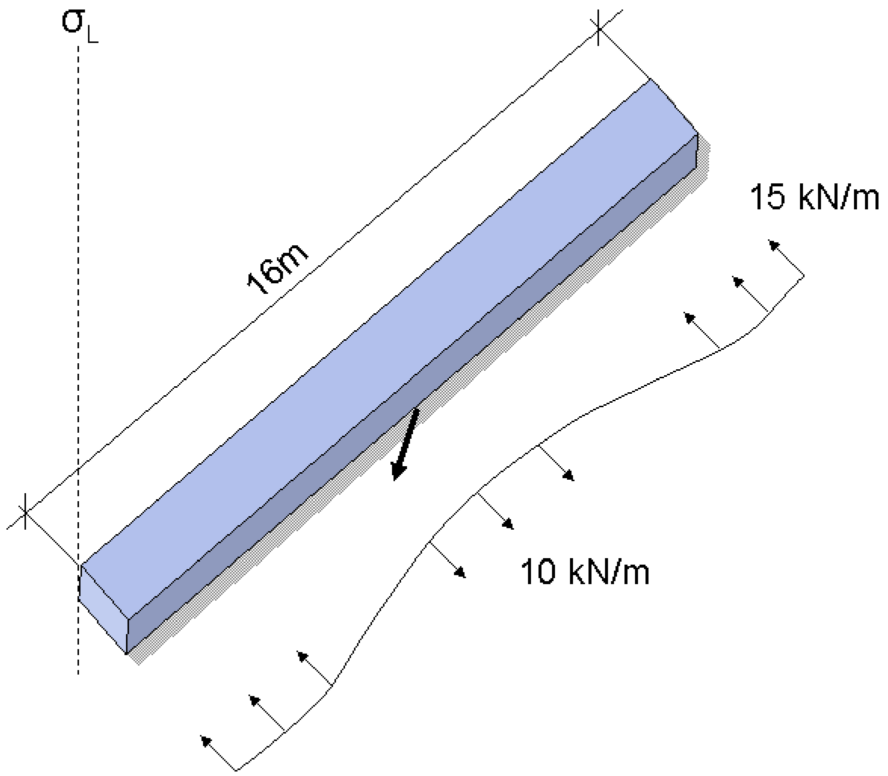

Figure 5 Wave load along Wave Device, seen from top.

The horizontal wave loads vary along the structure.

The forces towards the structure are a cosine with amplitude equal to 15kN/m and a length of 16 meter.

The forces acting away from the structure is again a cosine, but now the amplitude is only 10kN/m. Still the length is 16 meter.

The angle between the structure and the mooring force is 30 deg.

The vertical forces are shown on figure 6. The weight of the structure is assumed to be 0.55kN/m.

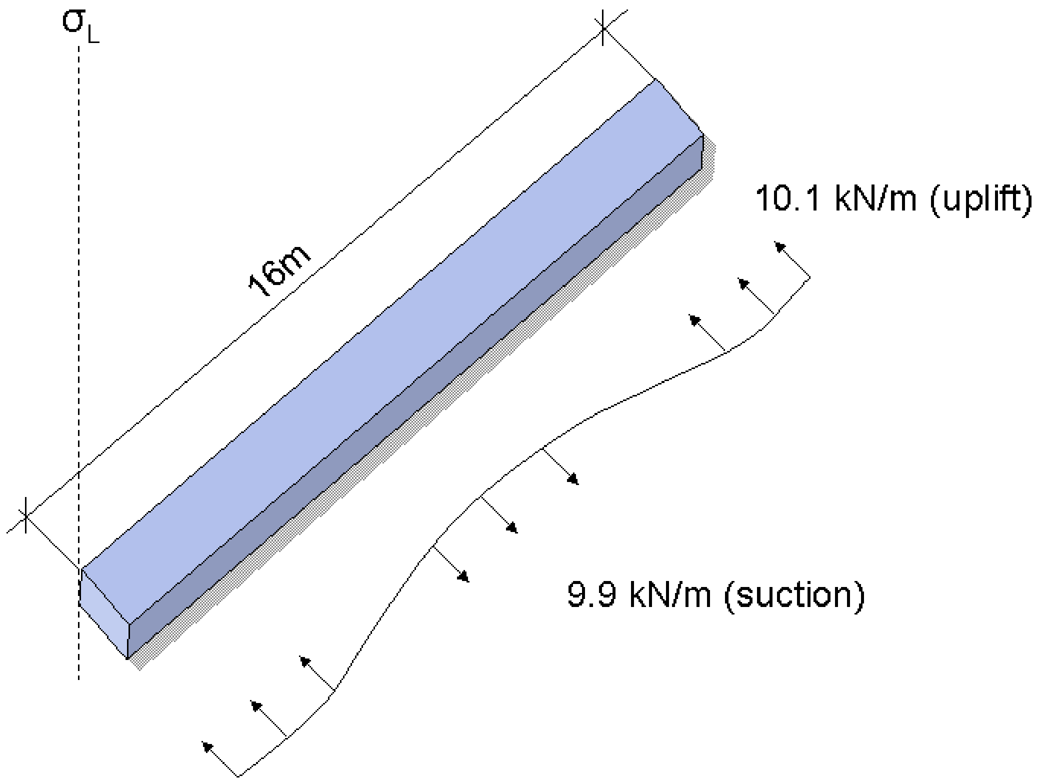

Figure 6 Vertical forces on the beam.

This vertical load will only occur in case of suction in the middle tubes. It may be too conservative.

A different way to look at the vertical loading is sketch in the following.

It is assumed the body of the LEANCON WEC follows the surface elevation of the waves. A section of the beam will then experience acceleration as indicated below.

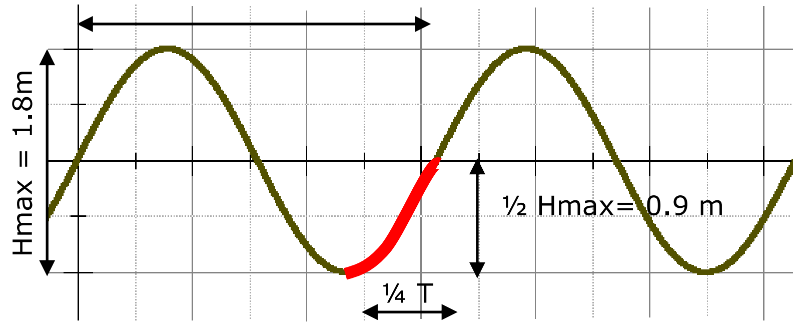

Figure 7 Section accelerated over 1/4th of a wave period.

Being the maximum acceleration represented by red line it will correspond to ¼ of Period T and ½ of the wave height, so ¾ s and 0.9m respectively.

As $S = 0.5*a*t^2$

Where: S = distance in meter and

t = time in seconds

$$a = \frac{S}{0.5 * t^2} \sim a = \frac{0.9}{0.5 * \left(\frac{3}{4}\right)^2} \sim a = 3.2 m/s^2$$

As F = m*a ~ F=0.55*3.2 ~ F=1.76kN

Using numbers referring Figure 6, another comparison analysis can be by the acceleration:

As $a = \frac{F}{m}$ ~ $a = \frac{9.9}{0.55}$ ~ $a = 18 m/s^2$

This indicates that the loads in Figure 6 probably are somewhat exaggerated when considering a floating structure.

3 Measurements on wave induced loads on single pipe section model

Model test setup

Results

Conclusions

4 Measurements on wave induced loads on 10 pipe section model

Model test setup

The 10 pipes model was subjected to several conditions of work considering Draft and Valve Setting under different regular and irregular waves as resumed on Table 4. A number of 54 regular wave samples were collected and 07 samples for irregular waves.

60 seconds were dedicated to each regular wave sample and 150 seconds to irregular wave samples, exception applied for the worst conditions H= 22.5 cm, T= 2.2 s and H= 25 cm, T= 2.3 s when 300 seconds were applied.

For each combination of Draught, Valve Setting, H and T a file structure was attributed under a standard T_XXX_YYY_Z_WW.dat, where:

T: Type of wave if **R**egular o **I**rregular;
XXX: Wave Height 000-250 (0,00 cm -25,0 cm);
YYY: Period time 000-230 (0,0 seconds – 2,3 seconds)
Z: Draught 0-9 cm
WW: Valve 00-25 (0 closed, 10 partial, 25 full open)
NN: Continuous number

It was assumed the wave incidence against the device is a line as the same of the tank water level in a constant distance 52 cm from M1 as showed on Figure 21. In practice it is not true as depending on the wave height the operation draught can considerably vary.

This constraint can be the cause of some residual force components on vertical axis found when comparing calculated and experimental results that should not exist. This explanation it's just a supposition and should be proved by new specific tests to verify those residual components sources to eliminate possible errors to the prototype.

Table 2 Conditions for tests on 10 pipe section- Resume

Regular Waves			
Draught (cm)	**Valve Setting**	**H (cm)**	**T**
4	0	2.1	0.9
		4.3	1.1
		6.6	1.3
		9.0	1.6
		11.5	1.8
		15.0	1.9
	10	2.1	0.9
		4.3	1.1
		6.6	1.3
		9.0	1.6
		11.5	1.8
		15.0	1.9
	25	2.1	0.9
		4.3	1.1
		6.6	1.3
		9.0	1.6
		11.5	1.8
		15.0	1.9
6	0	2.1	0.9
		4.3	1.1
		6.6	1.3
		9.0	1.6
		11.5	1.8
		15.0	1.9
	10	2.1	0.9
		4.3	1.1
		6.6	1.3
		9.0	1.6
		11.5	1.8
		15.0	1.9
	25	2.1	0.9
		4.3	1.1
		6.6	1.3
		9.0	1.6
		11.5	1.8
		15.0	1.9
8	0	2.1	0.9
		4.3	1.1
		6.6	1.3
		9.0	1.6
		11.5	1.8
		15.0	1.9
	10	2.1	0.9
		4.3	1.1
		6.6	1.3
		9.0	1.6
		11.5	1.8
		15.0	1.9
	25	2.1	0.9
		4.3	1.1
		6.6	1.3
		9.0	1.6
		11.5	1.8
		15.0	1.9
Irregular Waves			
Draft (cm)	**Valve Setting**	**H (cm)**	**T (s)**
6	10	7.9	1.3
		11.0	1.6
		14.4	1.8
		18.0	2.0
		20.0	2.1
		22.5	2.2
		25.0	2.3

Figure 8 shows the arrangement in the tank where M1 sensor was disposed at 52 cm and M2 at 37 cm from the water level. Those distances were used to obtain the calculated values to M1 and M2.

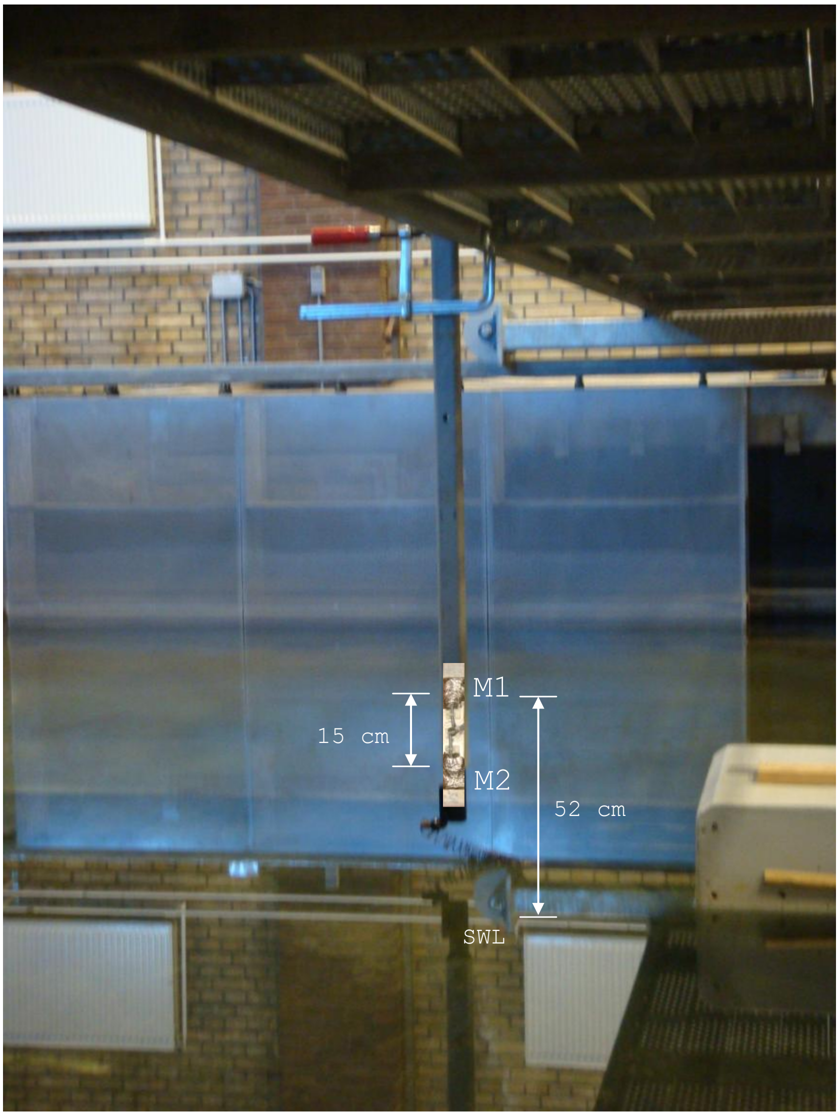

Figure 8 10 Pipes Model Test Arrangement. **NB! BUT THIS IS THE CREST WING!!**

Results

Figure 9 presents regression analysis for maximum, minimum and mean forces resulting from the irregular waves, supposed be the worst condition to the model, for constant value of Draught = 6cm and Valve Setting on half position.

The graphic of Figure 9 shows the highest irregular wave (H = 25cm) with longer period (T = 2.29s) offering the maximum positive and negative force to the device. For this specific wave it was plotted a graphic to show the force peak distribution in Figure 10.

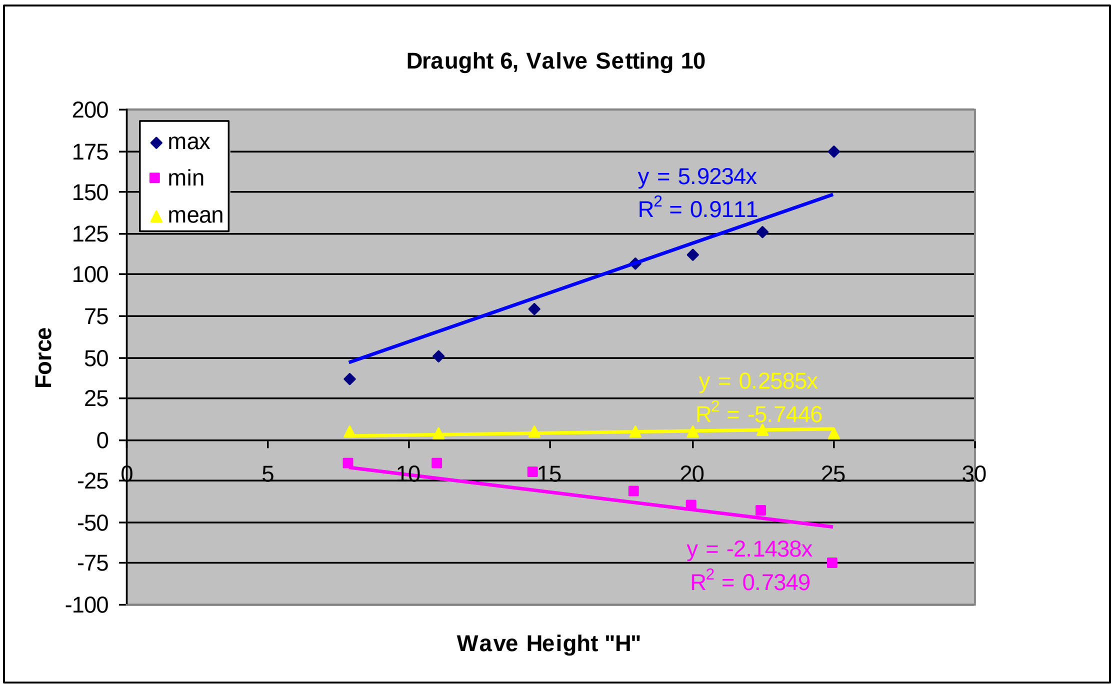

Figure 9 Irregular Waves Regression Analysis. **Here the force is 1/250, right – and the wave height is Hs. What are the units?**

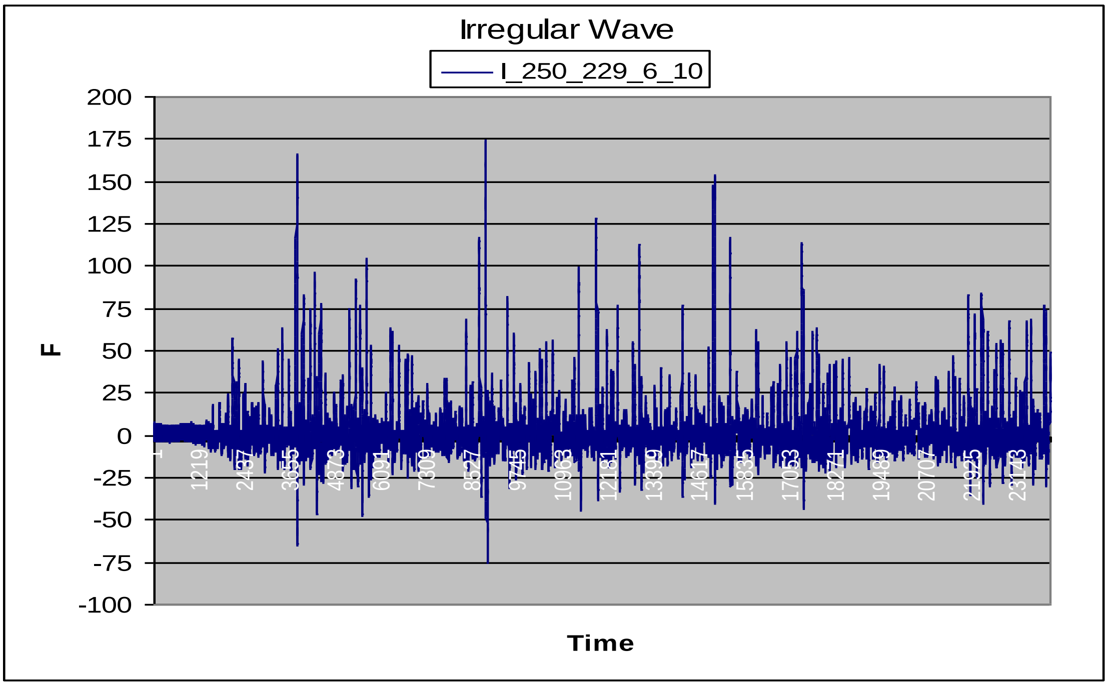

Figure 10 Force Peak Distribution - Irregular Waves (H=25cm and T=2.29s). **Units!**

For regular waves the values for maximum e minimum forces were plotted in a scatter graphic and a trend line set for each valve position and for each draught as well. The results are shown in Figure 11 to Figure 16.

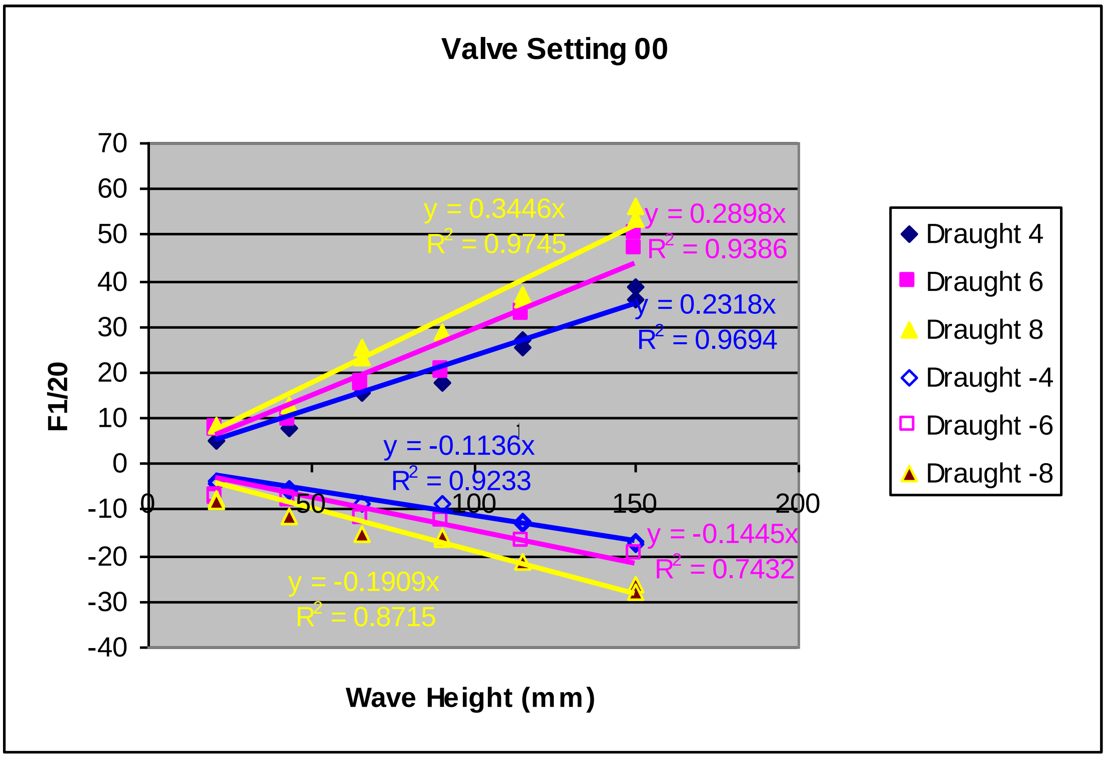

Figure 11 Regression Analysis for Valve Setting on 00.

Generally for these graphs: Write F instead of F1/20 on Y axis. Units!

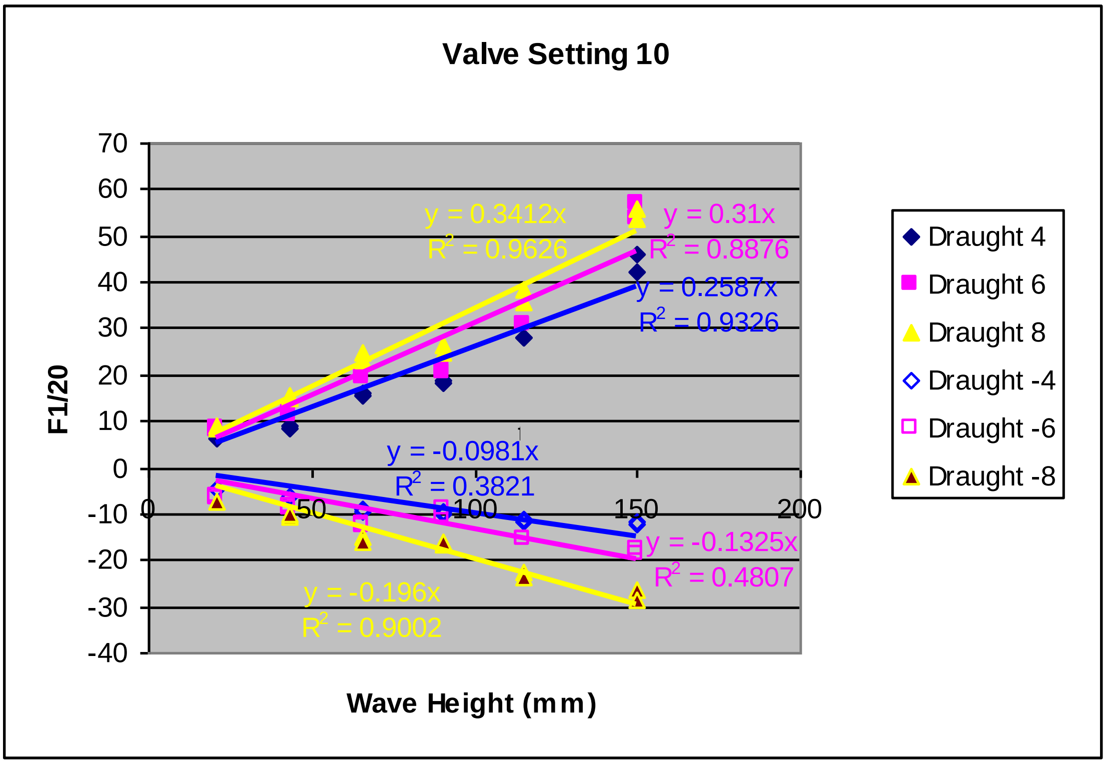

Figure 12 Regression Analysis for Valve Setting on 10.

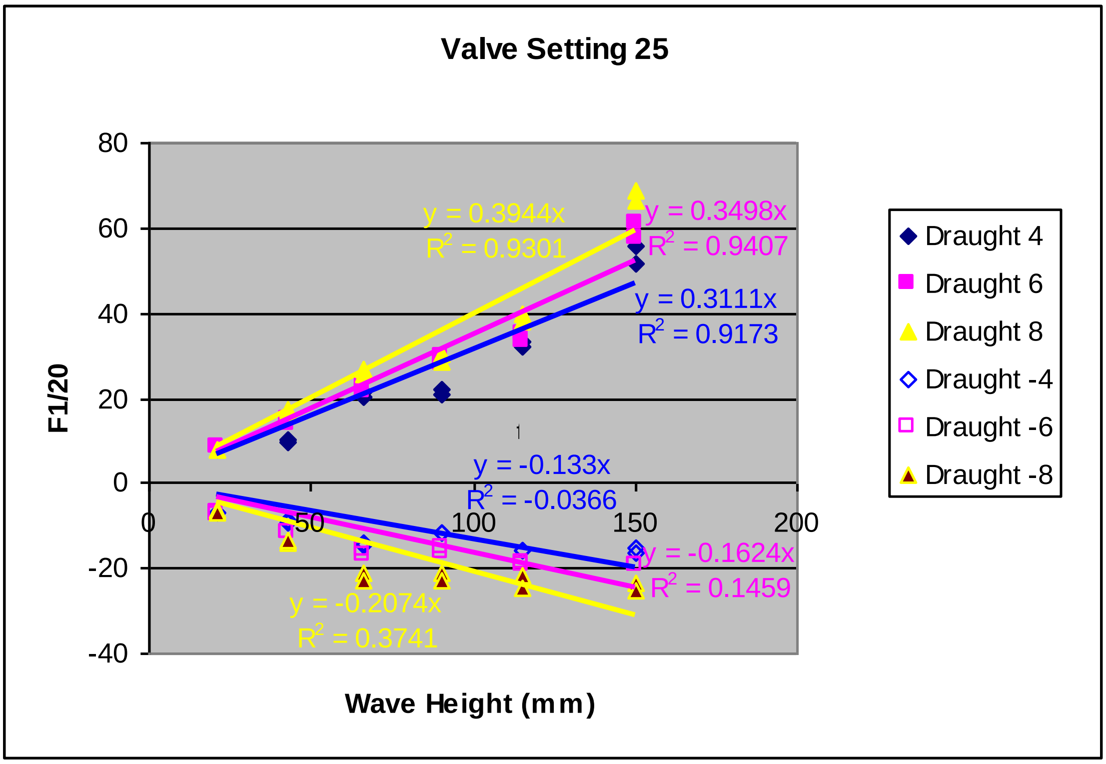

Figure 13 Force Regression Analysis for Valve Setting on 25.

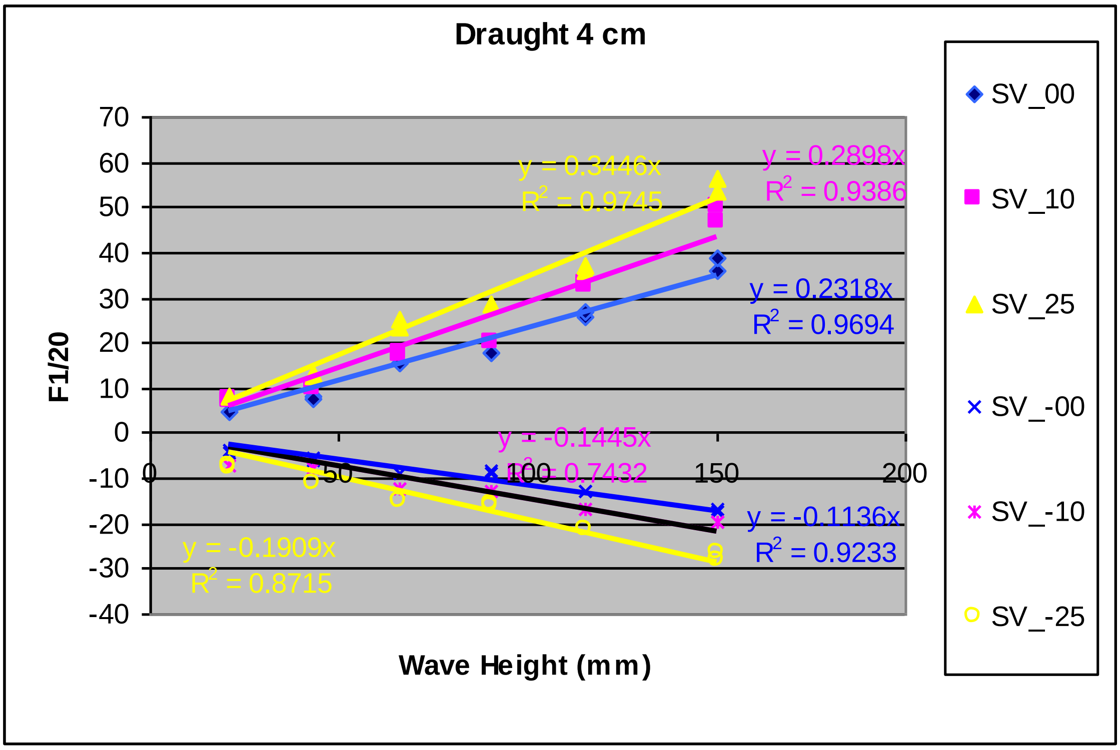

Figure 14 Regression Analysis for Draught of 4cm.

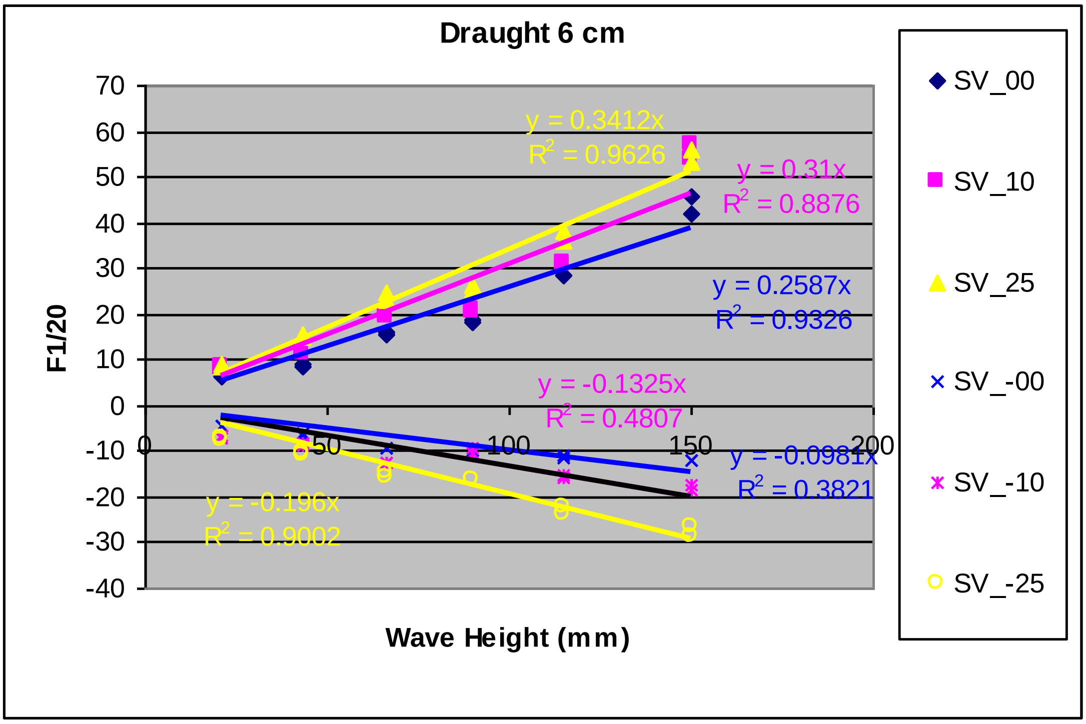

Figure 15 Regression Analysis for Draught of 6cm

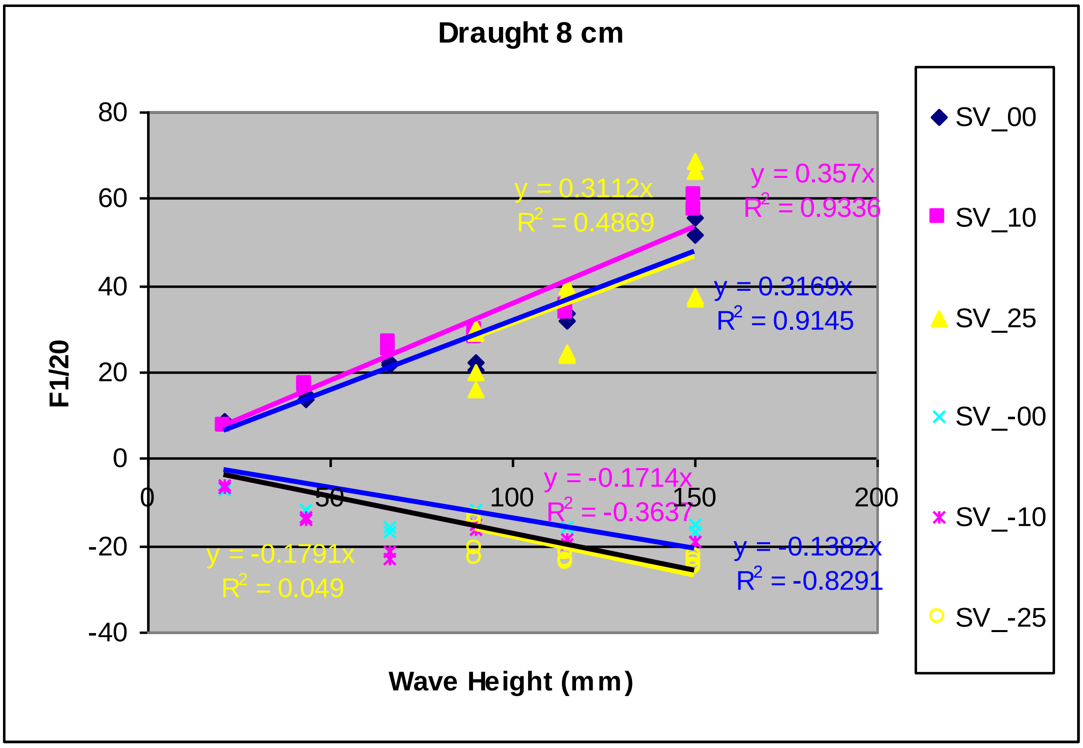

Figure 16 Regression Analysis for Draught of 8cm

Conclusions

From the performed model tests the following conclusions are drawn:

- The max. horizontal forces recorded compares …. to the loads estimated through the calculations in the previous section…..
- The lower the draught the higher the forces. Going from a draught of 4 cm to 8 cm increases the forces by approx. XX %.
- For the lower draughts (4 and 6 cm) the higher the valve setting (more closed valves) the higher the forces. For the largest draught of 8 cm the highest forces where found for the middle valve setting.

5 Conclusions

6 References

Bølgekraftudvalgets Sekretariat (Kim Nielsen), 1999: *Bølgekraft – forslag til forsøg og rapportering*. (61 pages in Danish). Published by Bølgekraftudvalgets Sekretariat / Danish Energy Agency, 1999.

Kofoed, J. P. & Frigaard, P.: *Hydraulic evaluation of the LEANCON wave energy converter*. DCE Technical Report No. 45. ISSN1901-726X. Dep. of Civil Eng., Aalborg University, Aug. 2008. Draft.

Appendices

Appendix 1: Calibration Test for a Single Pipe Model

The calibration test was performed using a single pipe model and 3 force sensors were disposed as showed by Figure 1 to measure vertical (F1 and F2) and horizontal (F3) forces.

To apply well defined loads over the model a set of 6 different standard weights of 50, 100, 200, 300, 400 and 500 grams were used at specified points and directions as stated in Figure 7. A measurement was done for 100 seconds time for each calibration.

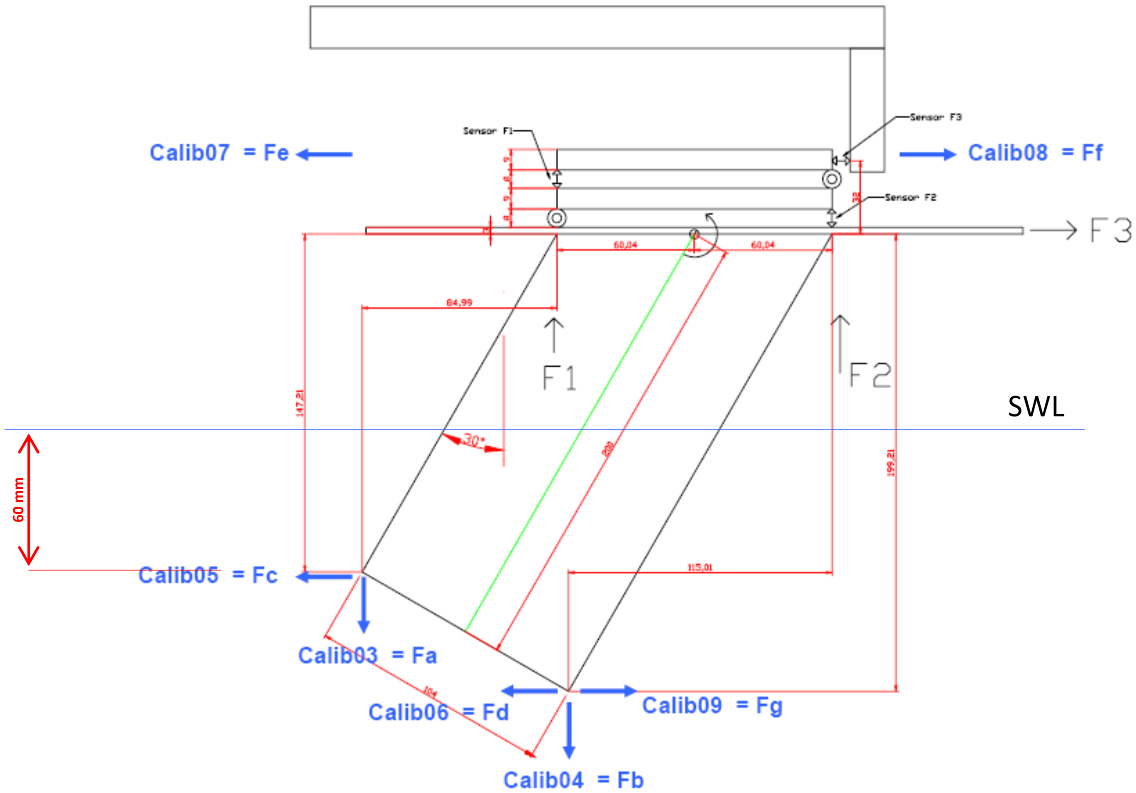

Figure 1: Schematic of sensors position and for a single pipe model calibration

Results acquired by the software for each calibration as illustrated by Figures 2-8 were confronted to that calculated ones of Table 1 using distances as disposed in Figure 1 and presented satisfactory similarity.

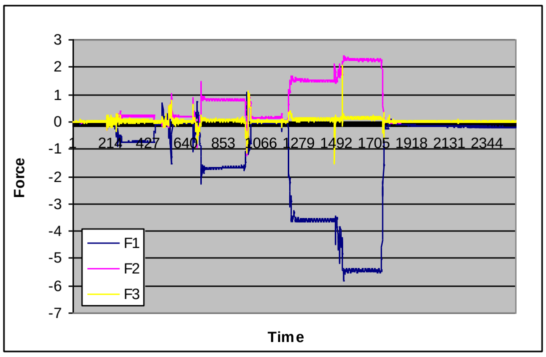

Figure 2: Calibration 03

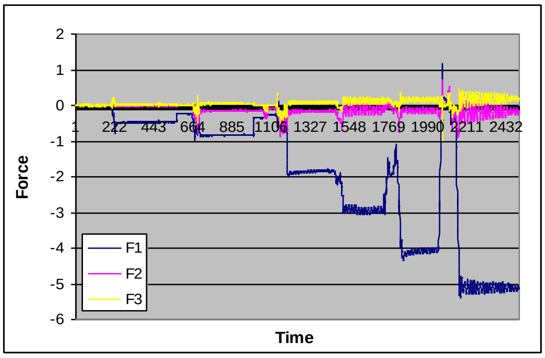

Figure 3: Calibration 04

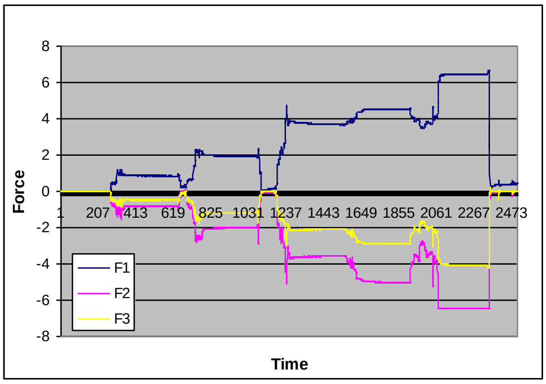

Figure 4: Calibration 05

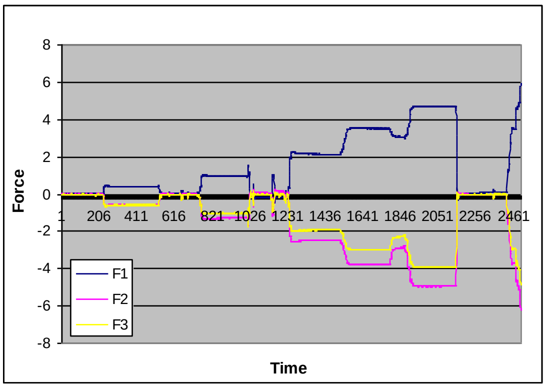

Figure 5: Calibration 06

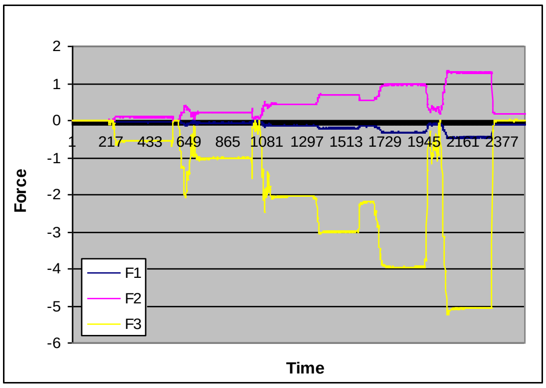

Figure 6: Calibration 07

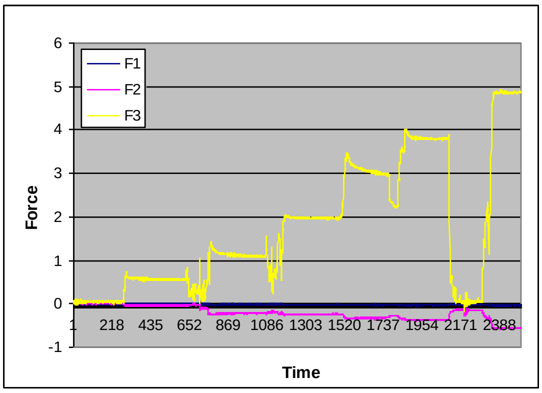

Figure 7: Calibration 08

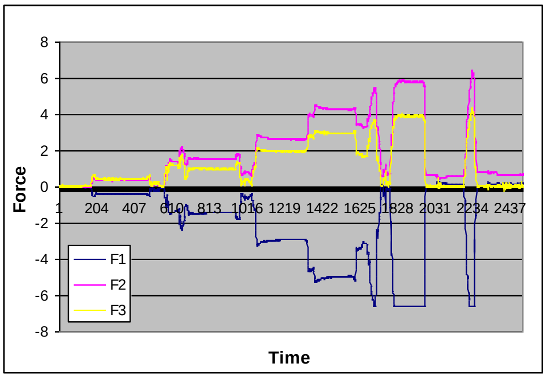

Figure 8: Calibration 09

Momentum caused by vertical Forces F1, F2 and horizontal force F3 are represented by colored lines on each calibration graphic in the Figures 2-8. To make an easier comparison between calculated and measured values the same color is assumed in the Table 2 for the force responsible for it. The grey color means no test was done for this specific value or was badly done and not valid.

Table 1: Calculated Momentum Forces for LeanCon Single Pipe Model

Forces Calibration		**Weight (g)**					
Calib.	**Force**	**50**	**100**	**200**	**300**	**400**	**500**
3	**F1**	-0.85	-1.71	-3.42	-5.12	-6.83	-8.54
	F2	0.35	0.71	1.42	2.12	2.83	3.54
	F3	0.00	0.00	0.00	0.00	0.00	0.00
4	**F1**	-0.48	-0.96	-1.92	-2.87	-3.83	-4.79
	F2	-0.02	-0.04	-0.08	-0.13	-0.17	-0.21
	F3	0.00	0.00	0.00	0.00	0.00	0.00
5	**F1**	0.61	1.23	2.45	3.68	4.90	6.13
	F2	-0.61	-1.23	-2.45	-3.68	-4.90	-6.13
	F3	-0.50	-1.00	-2.00	-3.00	-4.00	-5.00
6	**F1**	0.83	1.66	3.32	4.98	6.64	8.29
	F2	-0.83	-1.66	-3.32	-4.98	-6.64	-8.29
	F3	-0.46	-0.92	-1.83	-2.75	-3.66	-4.58
7	**F1**	-0.15	-0.29	-0.58	-0.87	-1.17	-1.46
	F2	0.15	0.29	0.58	0.87	1.17	1.46
	F3	-0.50	-1.00	-2.00	-3.00	-4.00	-5.00
8	**F1**	0.15	0.29	0.58	0.87	1.17	1.46
	F2	-0.15	-0.29	-0.58	-0.87	-1.17	-1.46
	F3	0.50	1.00	2.00	3.00	4.00	5.00
9	**F1**	-0.83	-1.66	-3.32	-4.98	-6.64	-8.29
	F2	0.83	1.66	3.32	4.98	6.64	8.29
	F3	0.46	0.92	1.83	2.75	3.66	4.58

Taking figure 2 as example where the result of calibration 3 is shown one can observe four peaks for vertical forces F1 (blue line) and F2 (red line) and as well a continuous yellow line of the horizontal force F3 around zero. The gap near zero between those peaks means the time while the weight was changed during the test rising so fast to stable values.

The calculated momentum from Table 2 for the same calibration 3 presents acceptable accordance to those values, negative values for F1, positive values for F2 and zero for F3. The stable values can be confronted as similar to that from the Table 2.

In general small differences between measurement and calculation can be eventually found but it's attributed to be considered F3 applied at the same point of the sensor for horizontal force where really is not promoting residual component force. Note it happens only to smaller values for each test keeping the highest one similar. For the purpose of this test to estimate the worst work condition to the device and qualitative impression of the force on it it's still valid.

Appendix 2: Calibration Test for a Ten Pipe Model

A test was performed to calibrate measurements on the 10 pipes model supported by an aluminum body contenting two sets of strain gages distant 15 cm one of the other where two momentum forces M1 and M2 were measured. Figure 1 illustrates the sensors disposition at the aluminum bar.

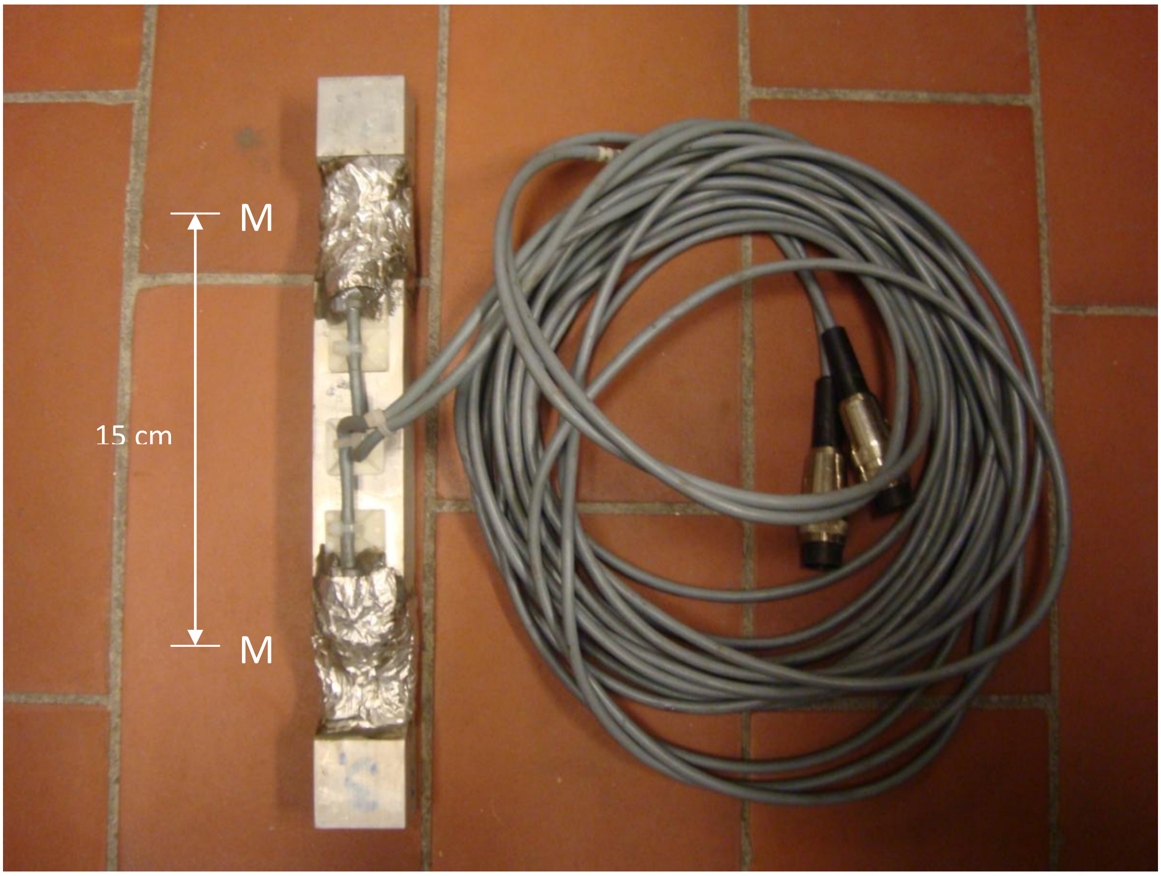

Figure 1: Strain Gages Disposal at the Bar

Before the model installation weights of 2, 4, 6, 10, 15 and 20 Kg were perpendicularly applied on the aluminum body at 25, 45 and 55 cm distant from the M1 point and samples were collected for 100 seconds. The calculated results for M1 and M2 are showed in Table 1 and graphics of figures 16, 17 and 18 were plotted to compare the results.

Table 1: Calculated Momentum Forces for LeanCon 10 Pipes Model

Distance	Mm	2	4	6	10	15	20
250	M1	5	10	15	25	37.5	50
	M2	2	4	6	10	15	20
450	M1	9	18	27	45	67.5	90
	M2	6	12	18	30	45	60
550	M1	11	22	33	55	82.5	110
	M2	8	16	24	40	60	80

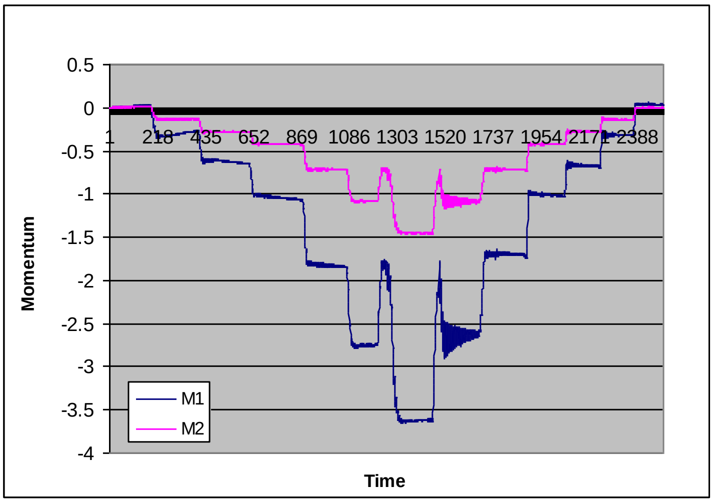

Figure 2: Measured M1 and M2 at 25 cm distant

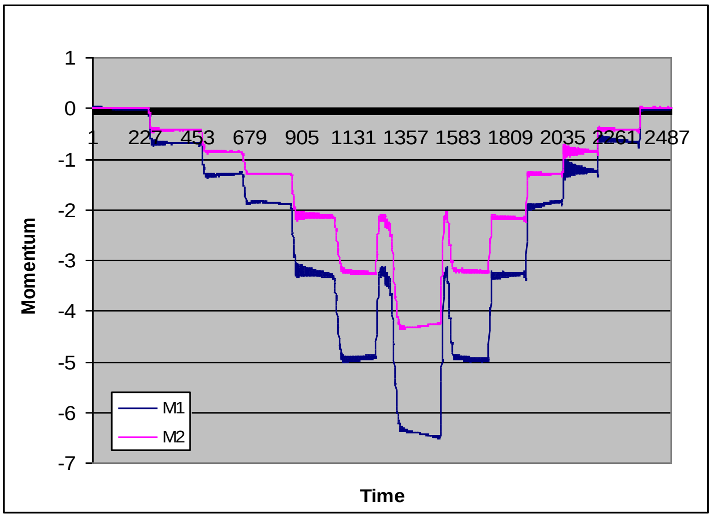

Figure 3: Measured M1 and M2 at 45 cm distant

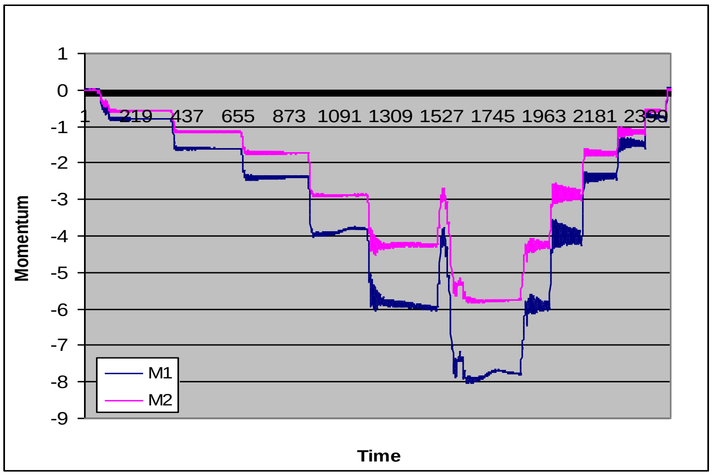

Figure 4: Measured M1 and M2 at 5½5 cm distant

To verify the accuracy between calculated and measured results was made a regression analysis showed on graphics of Figures 5 and 6 to evaluate the confidence.

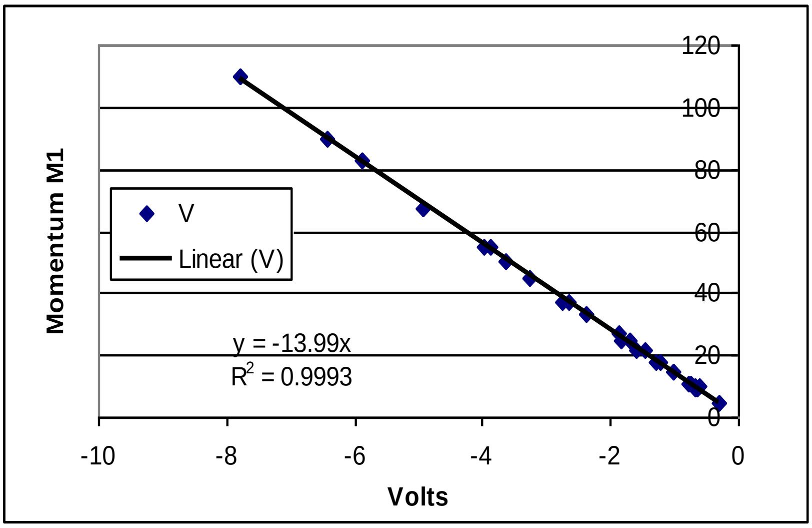

Figure 5: M1 Regression Analysis

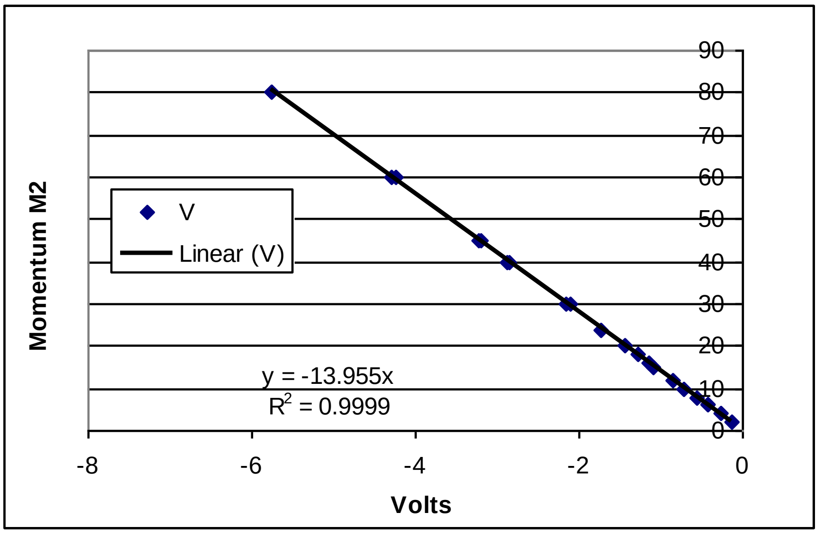

Figure 6: M2 Regression Analysis

M1 and M2 Regression Analysis presented a high level of correlation (R^2 more than 99%) for both, and a similar slop as well.