
# ETUDE EXPERIMENTALE D'UN SYSTEME DE CONVERSION DE L'ENERGIE DES VAGUES EXPLOITANT LES OSCILLATIONS D'UNE MASSE D'EAU CONTENUE DANS UN TUBE EN U

# *MODEL TESTS OF A WAVE ENERGY CONVERTER BASED ON WATER OSCILLATING IN A U TANK.*

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**Résumé**

L'objet de l'étude présentée dans cet article est la modélisation expérimentale en bassin d'un convertisseur d'énergie des vagues. Développé par l'IST (Instituto Superior Técnico), l'UGEN exploite les oscillations d'une masse d'eau contenue dans un tube en U embarqué à bord d'un flotteur. Ses mouvements induisent un flux d'air entre les deux branches du tube destiné à entraîner une turbine aérodynamique et ainsi capter une part de son énergie. Au contraire d'un système stabilisateur, les périodes propres du flotteur en roulis et du tube en U sont séparées afin d'amplifier les mouvements. Les résultats expérimentaux sont comparés à ceux d'un modèle numérique. Un jeu de quatre équations mettant en jeu l'embardée, le pilonnement et le roulis du flotteur et le mouvement d'eau interne est ainsi construit dans le domaine fréquentiel.

**Summary**

The paper presents the results of an experimental program with a scaled model of the UGEN wave energy converter (WEC). This concept has been developed by IST (Instituto Superior Técnico) based on a floating body with a U tank filled with water. The amount of water accounts for 40% of the floater displacement. The sway, heave and roll motion of the floating body coupled to the water oscillating in the U tube induce an oscillating air flow on the upper part of the U tank from one branch to the other through a circular tube. The aim of the device is to capture the air flow energy through a turbine. The natural period of the water in the U tank (circa 1.25 s) and of the resulting floating body natural rolling period (circa 1.9 s) are separated in such a way that the tank could not act as a stabilising device, but on the contrary could magnify the motions amplitudes. The experimental data is compared with results from a numerical model. The linear dynamics of the system is represented in the frequency domain by a set of four coupled differential equations of motion (sway, heave and roll motions of the floater, plus the motion of the water in the tank).

# 1 Introduction

The oceans have an enormous amount of renewable energy in the form of progressive waves, however, the conversion and utilization of this potential at reasonable costs is still a big scientific and technical challenge. The last 15 years have seen a large increase in the research and development effort in this area. Many concepts of Wave Energy Converters (WECs) have been proposed, investigated, some of them developed to the prototype phase, and at least one is initiating the commercial phase. Comprehensive reviews of the state of the art regarding methods of analysis, concepts of WECs and also the technologies involved, can be found in WaveNet (2003) and Nielsen et al. (2006, 2009).

The existing concepts can be classified according to the site location as: offshore (deep water) devices, near shore (shallow water) and shoreline devices. Most of the recent concepts consist of near shore floating systems for water depths up to around 80 m, but in average less than this. Near shore seastates are more energetic than shoreline ones, therefore the potential to capture wave energy is higher, while the offshore sites require more expensive mooring systems and connection to the power grid.

In terms of the principle for the wave energy extraction it is possible to classify the devices into: oscillating water column (either shore fixed or floating), absolute motion of a floating body against a fixed reference frame, relative motion of a floating multi-body, overtopping systems and devices based on deformable bodies. At present it can be said that none of the systems have demonstrated its technical and economical viability. It is not clear which of the existing concepts will prevail (or even if any of the concepts will prevail).

This work presents the results from an experimental program performed at the Ocean Engineering Basin of Ifremer with of a 1/16 scaled model of a new concept of a wave energy converter (WEC). The device is an asymmetric floating body with a large interior U tank partially filled with water. The energy is extracted from the oscillations of the U shaped water column. The objectives of the experimental program consist on: (a) characterize the dynamic behaviour of the oscillating water column in the U tank, (b) obtain experimental data to validate, or improve, the hydrodynamic numerical model of the wave energy converter. During the tests the model was moored with four lines based on linear springs ensuring a low natural frequency in surge, sway and yaw. The model was fitted with: force sensors connected to the mooring lines; pressure sensors, one on the top of each U tank branch; internal free surface sensors, two in each reservoir; targets for video tracking.

The testing program includes decay tests in order to evaluate the natural periods of oscillation and damping level and runs in regular and irregular waves in order to evaluate the transfer functions on various sea states. The power capture was simulated simplistically by a grid installed in the horizontal tube connecting the two upper parts of the U tank in order to induce a pressure loss. Three levels of pressure loss and associated damping were simulated.

# 2 The UGEN wave energy converter

The UGEN (floating device with a U tank for GENeration of electricity from waves) consists of an asymmetric floater with a large internal U tank filled with water, where the energy is extracted from the relative motion of the water inside the tank. Figure 1 shows a side view of the concept. The lateral reservoirs of the U tank are partially filled with water and the remaining with air, and the two lateral air compression chambers are connected by a tube with an installed turbine. The relative motion between the floater and the water column forces the air through the turbine which extracts the energy.

The floater rolling mode of motion is the main stimulator of the motion of the water in the tank, however the sway and heave motions are also coupled therefore the system has the potential to absorb the wave energy from three modes of motion. The device is kept in station with a slack mooring system and the natural period of the horizontal oscillations is much larger than the typical wave period. In terms of principle of energy conversion, this device can be classified as an Oscillating Water Column, however it differs from the existing concepts and it has several advantages: (a) the water column is totally interior therefore the system is completely closed and robust, the mass of the water column can be easily adjusted to tune the system to different sea states and it is possible to use freshwater with great advantages in terms of protection against corrosion (b) given the floater characteristics it is possible to couple the water column motion to the rolling motion, heave motion and sway motion, therefore the system has the potential to use three modes of rigid body motions to absorb the wave energy.

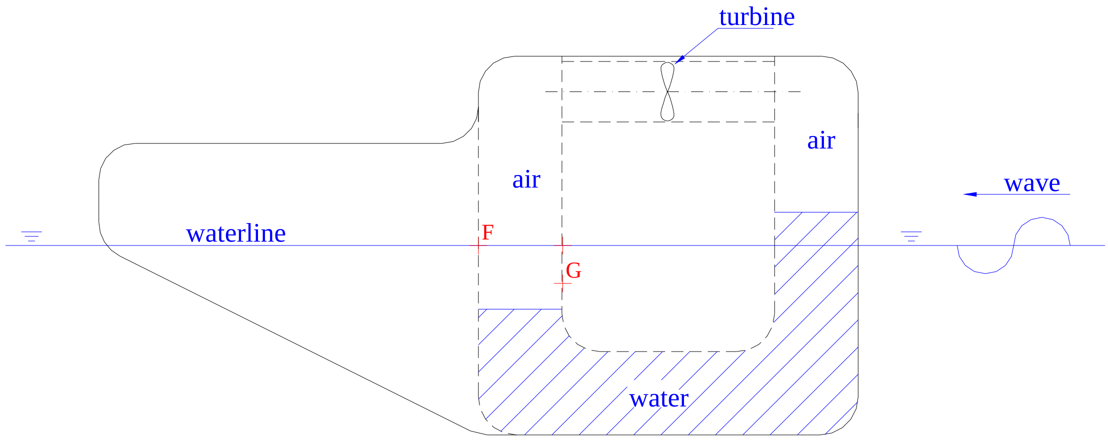


Figure 1 Side view of the UGEN wave energy converter

# 3 Numerical model of the UGEN

## 3.1 Theory

The hydrodynamic forces and motions are represented on a Cartesian coordinate system with origin on centre of gravity of the body, G, (figure 2). *y* is the longitudinal horizontal axis pointing to the incoming wave direction, z is positive upwards and *x* is perpendicular to the former. All degrees of freedom, $x_j$, $j$ =1,…6, are sequentially numbered according to standard convention. The vertical motion of the water in the U-tank reservoirs, $\delta h$, is represented by and additional rotational degree of freedom $x_7$ as represented in figure 2.

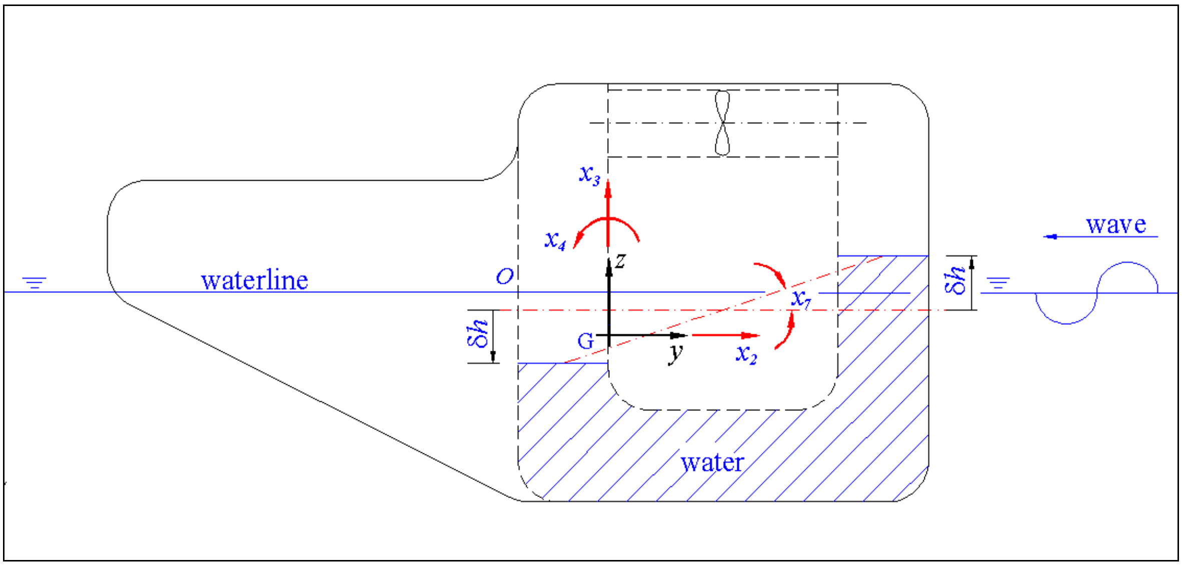


Figure 2 Coordinate system and convention for the motions.

Hydrodynamic coefficients and exciting forces of the WEC have been estimated by a standard 3D linear radiation-diffraction flat panel method, which has been applied in the form of the commercial WAMIT package. The method assumes potential flow, which satisfies the Laplace equation in the fluid domain, and a linear boundary value problem is formulated for the wave body interactions in incident harmonic waves. Green's theorem is used to derive integral equations with unknown velocity potential on the mean wetted body surface. The body boundary is discretized into a set of panels with constant potential on each panel, which results on a set of linear simultaneous equations in the unknown potentials.

The solution is found in the frequency domain. Details of the formulation and the discussion of some numerical aspects can be found in Lee and Newman (2004) and Lee (2007). The results are the added mass ($A_{kj}$) and damping coefficients ($B_{kj}$) for the six degrees of freedom rigid body motions ($x_j$, $j$ = 1,…,6), as well as the wave exciting forces in harmonic waves ($F_k^E$) along the six directions of the coordinate system ($k$ = 1,…6).

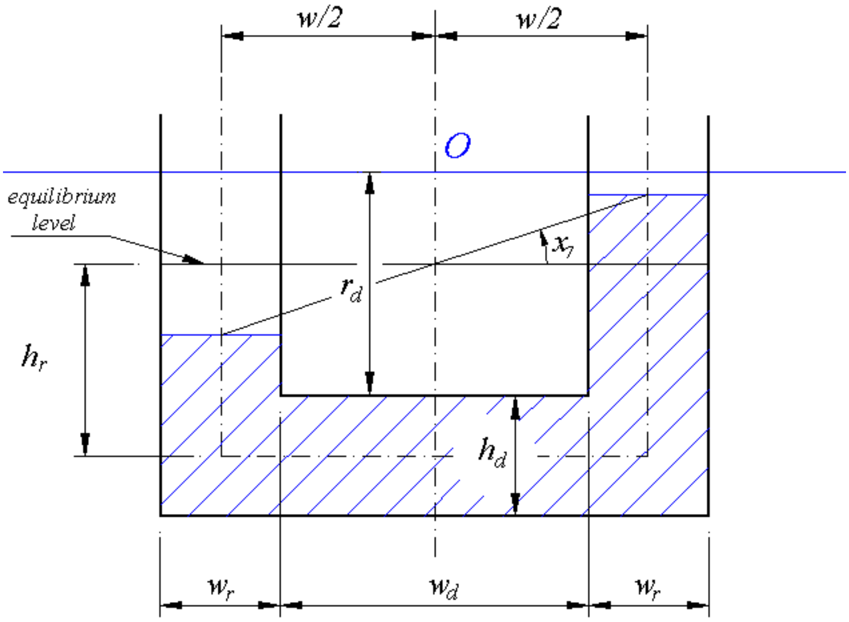


Figure 3 Passive U tank of Stigter's (1966) method

The dynamics of the 7th degree if freedom, consisting on the rotation of the body of water in the U tank, is represented by a simplified model based on the one-dimensional Euler equation. The method is based on the theory proposed by Stigter (1966) for the oscillations of U tube passive tanks to stabilize ship motions. A simplification of this theory is presented by Lloyd (1989), which is the method applied here. Consider the U tank of figure 3 with two reservoirs and a connecting duck with constant rectangular cross section. The length of the tank in the direction perpendicular to the cross section is $L_t$ . The equilibrium of forces in the fluid is represented by the (described above) one dimensional Euler equation evaluated along the middle line of the tank cross section. Assuming small rotation motions of the fluid, $x_7$, and integrating the Euler equation, one obtains the equation of fluid motion in the tank:

$$A_{77}\ddot{x}_7 + B_{77}\left(\dot{x}_7 - \dot{x}_4\right) + C_{77}x_7 + A_{72}\ddot{x}_2 + A_{74}\ddot{x}_4 + C_{74}x_4 + A_{76}\ddot{x}_6 = 0 \qquad (1)$$

The hydrodynamic coefficients are:

$$A_{77} = Q_t w_r \left( \frac{w}{2h_d} + \frac{h_r}{w_r} \right) \qquad (2)$$

$$B_{77} = Q_t q w_r \left( \frac{w}{2h_d^2} + \frac{h_r}{w_r^2} \right) \qquad (3)$$

$$C_{77} = Q_t g \quad (4)$$

$$A_{72} = A_{27} = Q_t \quad (5)$$

$$A_{74} = A_{47} = Q_t (r_d + h_r) \quad (6)$$

$$C_{74} = C_{47} = Q_t g \quad (7)$$

$$A_{76} = A_{67} = -Q_t L_t \quad (8)$$

$$Q_t = \frac{\rho w_r w^2 L_t}{2} \quad (9)$$

where $q$, $g$ and $\rho$ are respectively the coefficient of resistance of the tank to the water motion, the acceleration of gravity and the density of the water in the tank.

The UGEN wave energy converter is symmetric about the *y-axis*, therefore, since we consider harmonic waves along this direction, the only degrees of freedom will be the sway ($x_2$), heave ($x_3$), roll ($x_4$) and the motion of the water in the tank ($x_7$). The four coupled equations of motion are:

$$\begin{cases} [M + A_{22}]\ddot{x}_2 + B_{22}\dot{x}_2 + A_{23}\ddot{x}_3 + B_{23}\dot{x}_3 \\ \qquad + [A_{24} - Mz_G]\ddot{x}_4 + B_{24}\dot{x}_4 + A_{27}\ddot{x}_7 = F_2^E(t) \\ A_{32}\ddot{x}_2 + B_{32}\dot{x}_2 + A_{33}\ddot{x}_3 + B_{33}\dot{x}_3 + C_{33}x_3 \\ \qquad + [A_{34} + My_G]\ddot{x}_4 + B_{34}\dot{x}_4 + C_{34}x_4 = F_3^E(t) \\ [A_{42} - Mz_G]\ddot{x}_2 + B_{42}\dot{x}_2 + [A_{43} + My_G]\ddot{x}_3 + B_{43}\dot{x}_3 + C_{43}x_3 \\ \qquad + [A_{24} + I_{44}]\ddot{x}_4 + B_{44}\dot{x}_4 + C_{44}\xi_4 - A_{47}\ddot{x}_7 + C_{47}x_7 = F_4^E(t) \\ A_{77}\ddot{x}_7 + (B_{77} + B_{pto})(\dot{x}_7 - \dot{x}_4) + C_{77}x_7 + A_{72}\ddot{x}_2 + A_{74}\ddot{x}_4 + C_{74}x_4 = 0 \end{cases} \quad (10)$$

In addition to the coefficients already defined, $C_{kj}$ represent the restoring coefficients, $Z_G$ and $Y_G$ are the vertical and horizontal position of the total centre of gravity with respect to the origin of the coordinate system, $M$ is the total mass, $I_{kj}$ represent the moment of inertia coefficients and $B_{pto}$ represents the linearized damping coefficient of the power take off system. The equations of motion are solved in the frequency domain to obtain the motions' transfer functions.

# 4 Wave tank testing

## 4.1 Tank experimental facilities

Wave tank testing of a *1/16* scale model of the wave energy converter has been performed in the ocean engineering basin at Ifremer (Figure 4) from 19th to 29th April 2010. The deep wave basin of Brest has the following characteristics: length = *50 m*, width = *12.5 m*, depth = *20 m* by *12.5 m* and = *10 m* by *37.5 m*.

Regular and irregular are generated by the wave-maker in one end of the basin and damped by the artificial beach on the opposite end. Moreover, one-way swell with maximum amplitude peak-trough of *45 cm* can be generated by this wave-maker and beach without interference effects. The towing carriage of models can move at varying speeds up to *1.5 m/s*. Additional handling facilities are provided by cranes of *25* and *5 ton*.

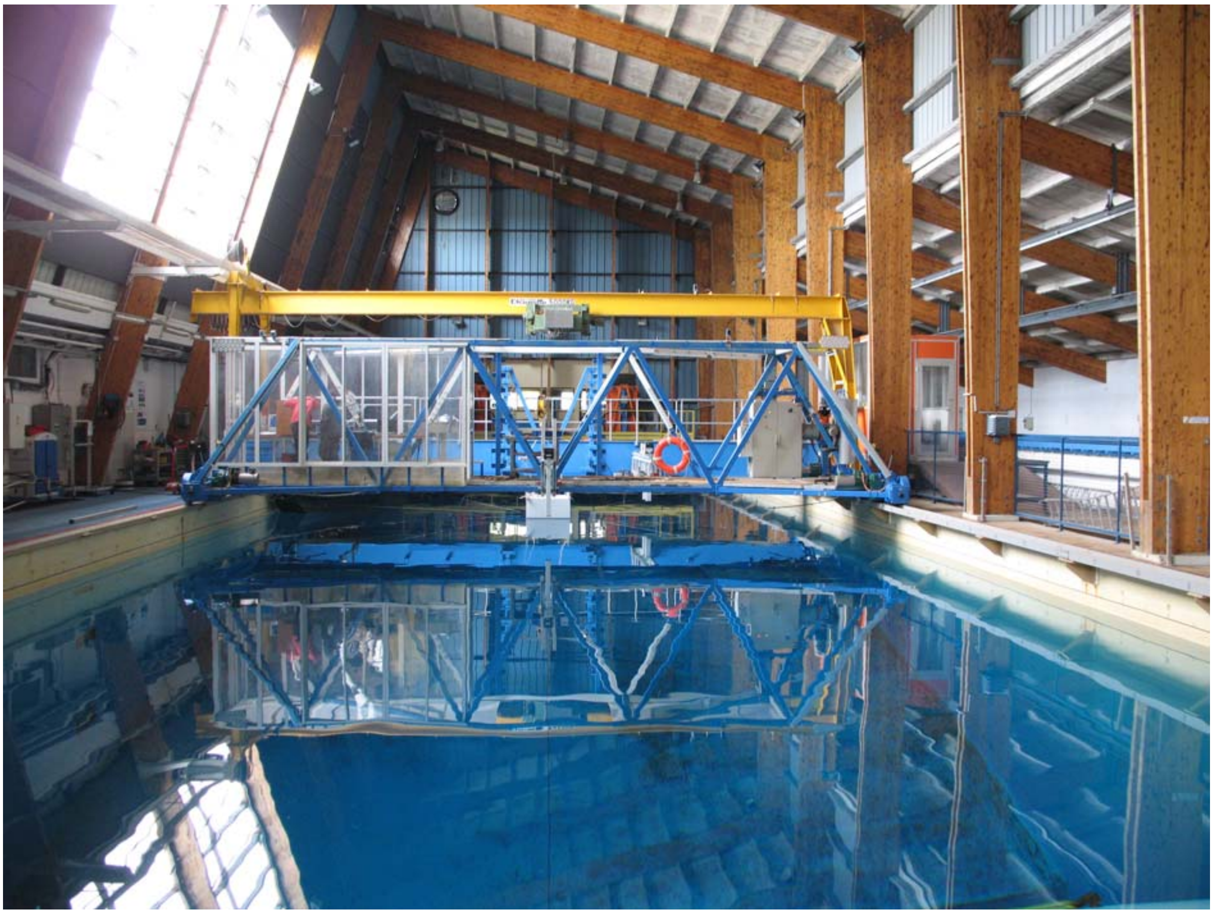

Figure 4:  View of experimental facilities at IFREMER.

### 4.2 Instrumentation

A data acquisition system, consisting of a National Instruments™ NI-6229 USB board and a laptop with a LabView™ program, was used to measure and record signals at *100 Hz* from an array of sensors set up on the model.

The model was fitted with the following sensors:

- Four force sensors connected to the mooring lines, where classical "S-type" force sensors were used on the model to measure the mooring lines tensions;
- Two pressure sensors, one on the top of each lateral reservoir of the U tank, where pressure sensors 143PC01D HoneyWell Microswitch were utilised to monitor the pressure in each air chamber of the U tube;
- Four internal free surface sensors, two in each lateral reservoir of the U tank. These are capacitive type water elevation gauges, made of two wires partly immersed in the water with one of the wires fully isolated;
- Six targets for video tracking and a Videometric™ system was used to track the 3D motions of the model. The system consists of markers (black circles on white squares, as shown in Figure 5) set up on the model, a couple of cameras mounted at each end of a horizontal metallic beam and a desktop computer. The 3D motion is calculated from the 2D coordinates of each marker, recorded by each camera. The six degrees of freedom of the rigid body are given within an uncertainty of *0.1 deg* for rotations and *0.5 mm* for translations. The measuring frequency is *25 Hz*.

Several sensors recorded as well the incident and disturbed waves. Servo type wave gauges have been utilized to measure wave elevation in the basin. For this kind of wave gauges, a detector on the lower end of a moving rod detects the immersion of the probe tip in the water. If immersed it makes the rod to move upward, out of the water. If the tip loses the contact with the water the detector switches the rod to a downward motion until the probe tip is re-immersed. The switching process is very fast and the movement of the tip effectively follows the wave surface.

Finally, video recording by means of air and underwater analogical cameras were used to grab sequences of the trials. The two cameras views were mixed together and recorded on laptop.

### 4.3 Tests programme

The experimental activities at Ifremer were extensive and highly resources consuming, and therefore can be divided into five main groups:

- Group of Activities Nr. 1 - Initial Setup Model Tests;
- Group of Activities Nr. 2 - Internal Damping Tests;
- Group of Activities Nr. 3 – Static Tests in Calm Water: Mooring Stiffness, and Model's Stiffness Characteristics;
- Group of Activities Nr. 4 – Dynamic Free-decay Tests in Calm Water: Mooring Natural Frequencies and Damping, and Model's Natural Frequencies and Damping Characteristics;
- Group of Activities Nr. 5 - Regular and Irregular Waves Tests.

### 4.4 Characteristics of scaled model

The main dimensions of the scaled model (*1:16*) are: length = *1.25 m*, width = *0.937 m*, height = *0.75 m*, draft = *0.3125 m*. As shown in Figure 3, the model was manufactured in white opaque fibre glass reinforced plastic (FGRP), except in the aft end of the U tank, where semi-transparent FGRP has been applied to allow visualization of the water free-surface inside the tank. Between the two lateral reservoirs a FGRP horizontal pipe of *100 mm* diameter has been installed to connect both air chambers. In order to allow simulation of the dynamic effect of a Power Take-Off (PTO), in the middle section of this tube an insert was made to install different types of grids, which induced different levels of pressure loss. Cargo holds are provided inside the model to accommodate and fix several lead blocks of ballast.

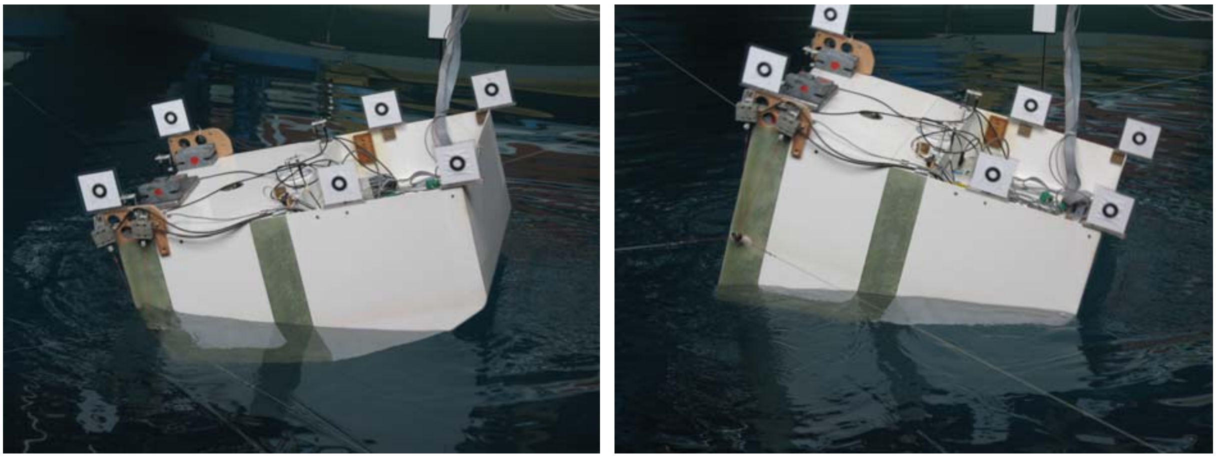

Figure 5: View of floater's waves induced motion, where the green-gray area shows the location of the U tank.

As shown in Figure 5, the model was moored to the sides of the wave basin with four segmented-lines (two fore and two aft on each side) made of polymeric cables and linear springs, thus ensuring a low natural frequency in surge, sway and yaw.

Table 1 presents the main particulars of the model together with the mass, damping, inertia properties and the system natural periods. The inertia was determined with bifilar pendulum tests. The centre of gravity was measured with stability tests in calm water. Decay tests were carried out to estimate the damping factors of the different modes of rigid body motions and fluid in the tank oscillations, as well as the corresponding natural periods. Full scale data is given on table 1 as well.

Table 1: Main particulars of the WEC and system characteristics from experimental tests.

| | Model Scale | Full Scale |
|---|---|---|
| Scale | 1:16 | 1:1 |
| Length (m) | 1.250 | 20.0 |
| Width (m) | 0.937 | 15.0 |
| Depth (m) | 0.750 | |
| Draft (m) | 0.3125 | 5.0 |
| Mass total (kg) | 287.5 | 11.78e5 |
| Mass in U Tank (kg) | 119.3 | 4.89e5 |
| Roll inertia ($kgm^2$) | 12.890 | 13.52e6 |
| ZG(m) from base line | 0.312 | 5.0 |
| Roll damping factor | 0.002 | 0.002 |
| U tank internal roll damping factor 1* | 0.008 | 0.008 |
| U tank internal roll damping factor 2* | 0.060 | 0.060 |
| U tank internal roll damping factor 3* | 0.120 | 0.120 |
| Roll natural period (s) | 1.86 | 7.44 |
| Sway natural period (s) | 18.84 | 75.4 |
| Surge-yaw coupled natural period (s) | 18.65 | 74.6 |
| Period of water inside the tank (s) | 1.25 | 5.0 |

**Note: damping factors 1, 2 and 3 correspond to the open tube between the reservoirs, intermediate damping grid and large damping grid.*

# 5 Experimental results and analysis

## 5.1 Methods for experimental data analysis

This section explains the methods used for the analysis of the experimental records. In regular waves several wave periods are selected within the range where the response is considered as stationary. The selected time records are Fourier analyzed and the Discrete Fourier Transform is also calculated. The results are the mean values and the five first harmonics of the periodic time trace. Figure 6 presents an example of analysis for a regular wave with a model scale period of 1.9s and wave amplitude of 4.7cm. The six degrees of freedom motion harmonics are presented on a frequency scale.

For irregular waves, each wave spectrum has been calibrated without the model in the tank. A set of amplitudes is selected and random phases are associated to the amplitudes. Different irregular time series can be generated for a given couple of spectrum parameters (*Tp*, *Hs*) by changing the uniformly distributed random phases. For the analysis, a pseudo-period is considered within the time range of fully developed seastate at the tank position of measurements. The pseudo-period is 300s at model scale (20 minutes at full scale). The Fourier analysis is carried out to obtain the power density spectrum, while the transfer functions are computed as the quotient of the cross power spectral density of each channel and the power spectral density of the reference channel (incident waves).

For decay tests of a given parameter (motion, free surface elevation, or pressure), an analysis is run on a sliding time interval in order to determine the natural period and time decay value and analyse their variations toward the parameter amplitude or velocity.

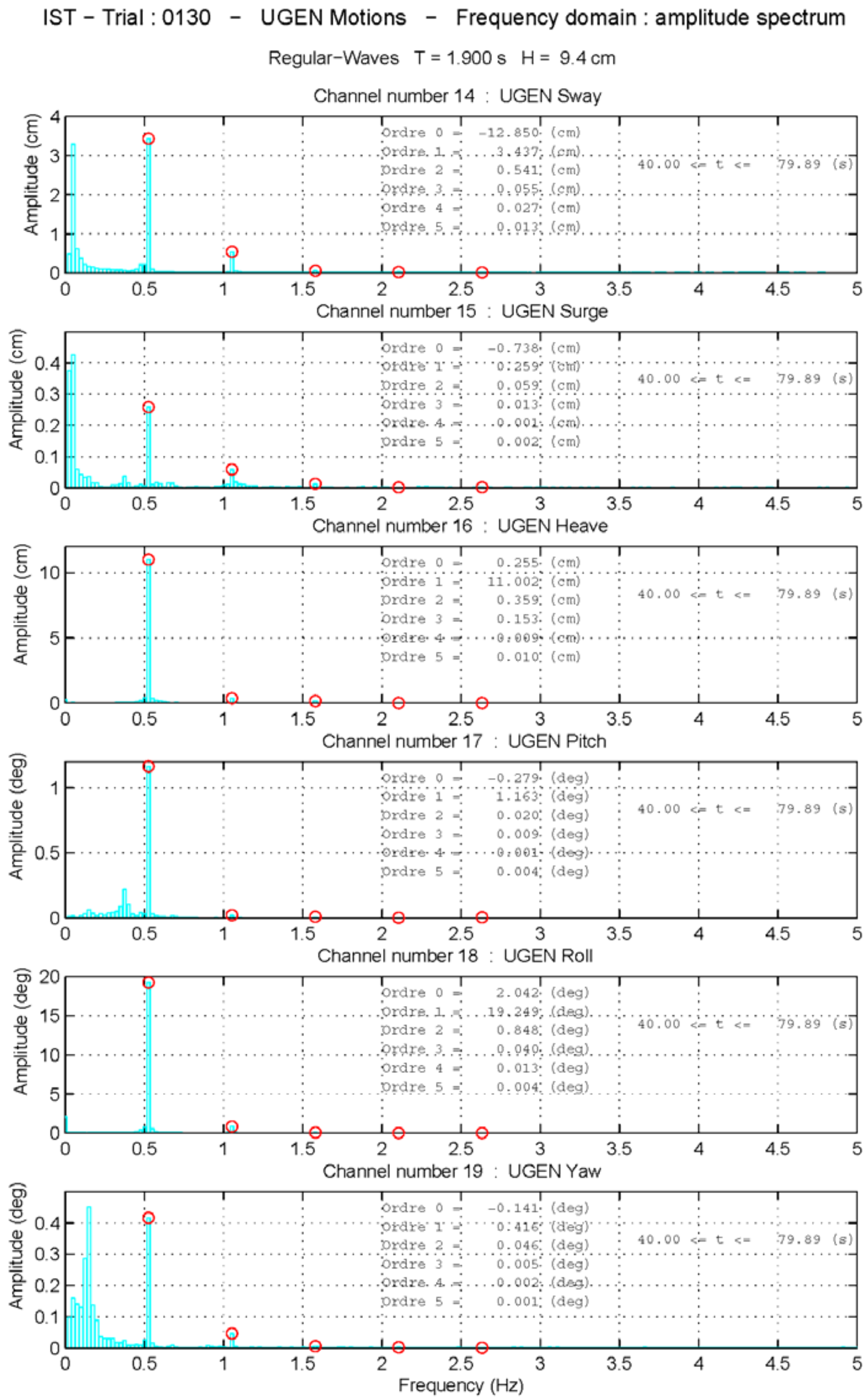


Figure 6 Amplitude spectrum in regular waves with period of 1.9s and wave amplitude of 4.7cm. Discrete Fourier Transform (cyan bars) and Fourier series (red circles). (Model scale).

## 5.2 Regular wave tests

Tests in regular waves have been carried out to obtain the transfer functions for three different settings for the U-tank damping. The first setting corresponds to the open tube between the two reservoirs and the corresponding damping factor for the water column motion is 0.008.

The other settings correspond to damping factors of 0.060 and 0.120. The damping factors were estimated from free decay tests. The objective is to assess the influence of the tank damping on the motion amplitudes. Figure 7 presents the graphs with the motion transfer function amplitudes for the three damping factors (different symbols correspond to different damping ratios). These amplitudes are defined by the ratio between the first harmonic of the motion response and the first harmonic of the incident wave. In this series of tests the incident wave steepness was kept constant at $k\zeta_a$ = 0.052 which corresponds to small amplitude waves ($k$ is the wave number and $\zeta_a$ the wave amplitude). The results are for the full scale WEC and they are presented as function of the incident wave period. All forthcoming results will be presented for the full scale.

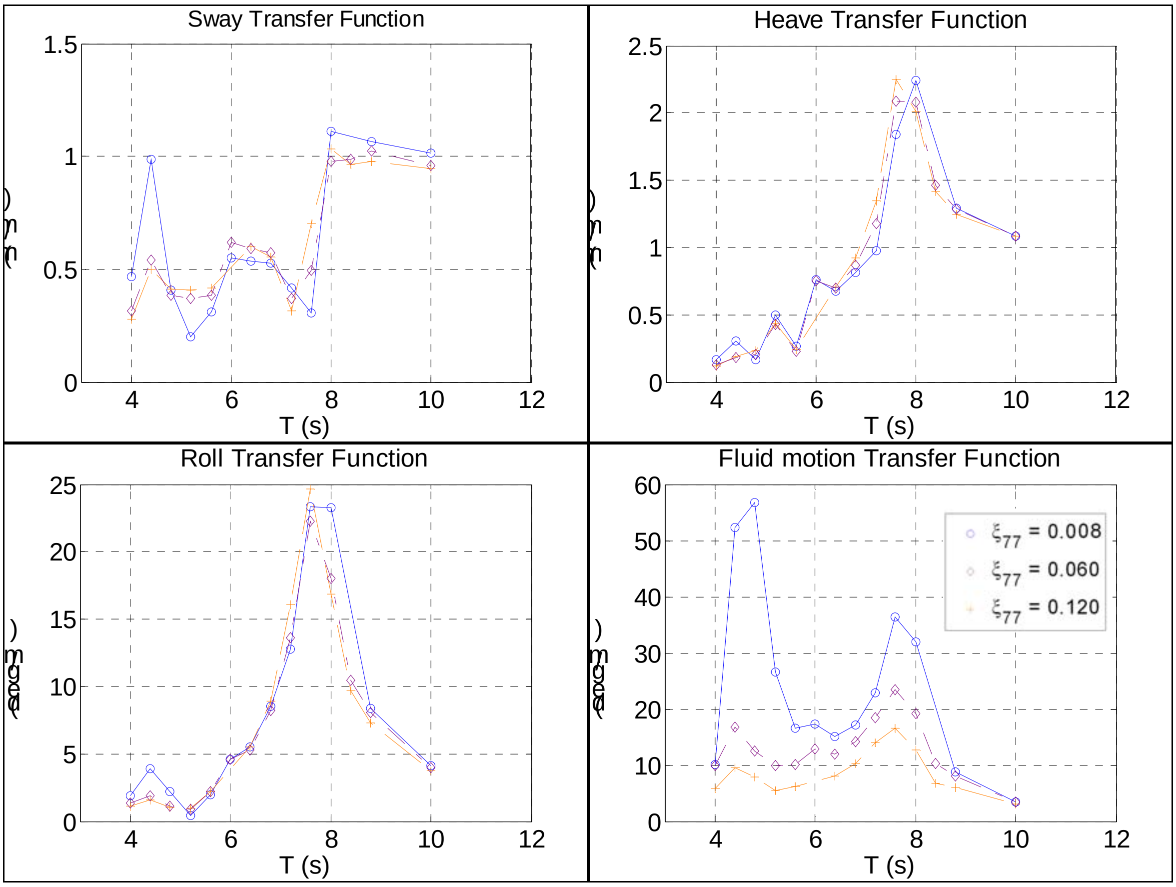


Figure 7 Transfer function amplitudes obtained in regular waves for three damping factors of the fluid motion in the tank (regular waves with steepness $k\zeta_a$ = 0.052)

It is possible to identify clearly two distinct frequency ranges with large dynamic amplification of the fluid motion in the tank. The first, at around 4.8s (at full scale), is related to the natural period of the oscillating water column it self. The second one occurs around the rolling motion natural period of 7.8s. It is important to design the system so that these two natural periods are different, otherwise the U tank motions will stabilize the rolling motion and therefore the potential to absorb energy will decrease. The two peaks of the tank transfer function are beneficial in irregular waves since they widen the frequency range of wave energy capture.

One also observes that the sway motion is strongly coupled to the tank motion and both the sway and heave are coupled to rolling motion. For these reason the UGEN WEC has the potential to extract the wave energy from three modes of rigid body motions. Regarding the effects of the tank damping, meaning the setting of the power take off, one concludes that the fluid motion reduces very much as the damping factor increases. There is some influence on the other transfer function amplitudes around the tank natural period of 4.8s, but overall we can say that, within the tested range of damping, tank damping has a small effects on the sway, heave and roll motions of the rigid body.

Figure 8 shows the transfer function amplitudes of the same motions, however in this case the damping factor of the tank is kept constant at 0.008 and three sets of results correspond to three wave steepnesses, namely $k\zeta_a$ = 0.052, 0.079 and 0.157. There is a clear reduction of the transfer function normalized amplitudes, especially for the rolling and tank motions around the resonance peaks. The decrease of these peaks with the increasing wave amplitude is around 20% to 30%. This indicates that these responses are slightly nonlinear.

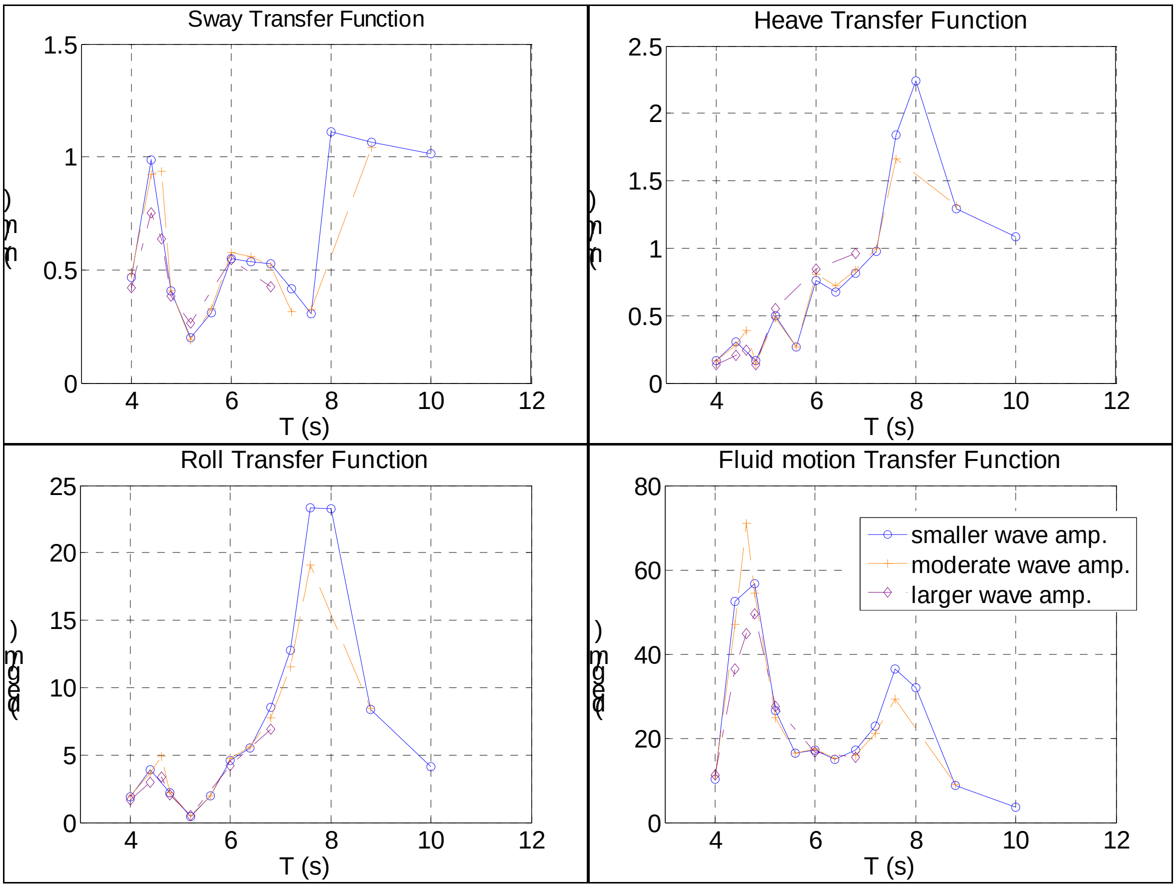


Figure 8 Transfer function amplitudes obtained in regular waves for three wave steepnesses (U tank fluid motion damping factor of 0.008)

## 5.3 Irregular wave tests

The tests in irregular waves were carried out for three seastates with the following significant wave heights and peak periods (*Hs*, *Tp*) = (1.50m, 7.1s) ; (2.50m, 9.7s) ; (3.50m, 11.0s.). Each seastate was run for the three of the tank damping defined in 4.2. Figure 9 to 11 present the transfer function amplitudes obtained from Fourier analysis of the irregular time records (colored lines for different seastates). Each figure corresponds to one setting of the tank damping and the regular wave results from the smaller amplitude waves are plotted together, with the symbols, for comparison.

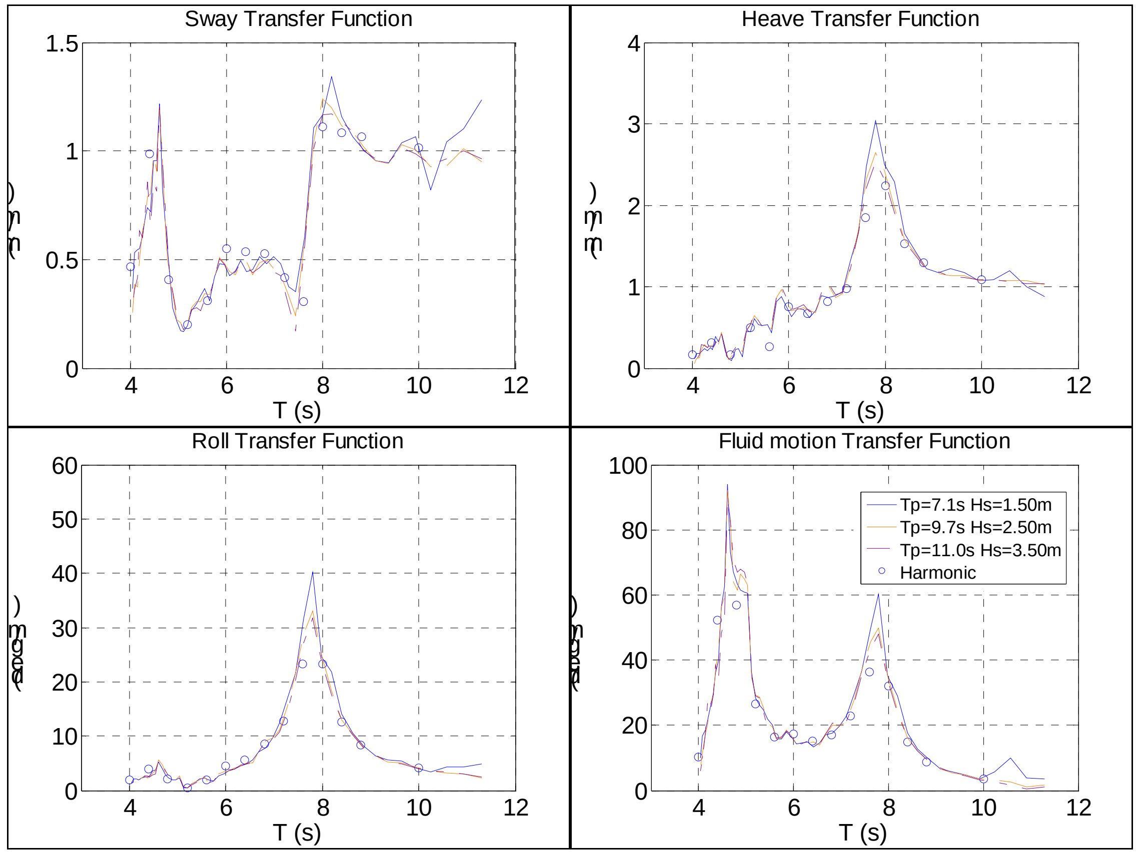


Figure 9 Transfer function amplitudes obtained from regular waves and from irregular waves. Fluid motion damping factor of 0.008.

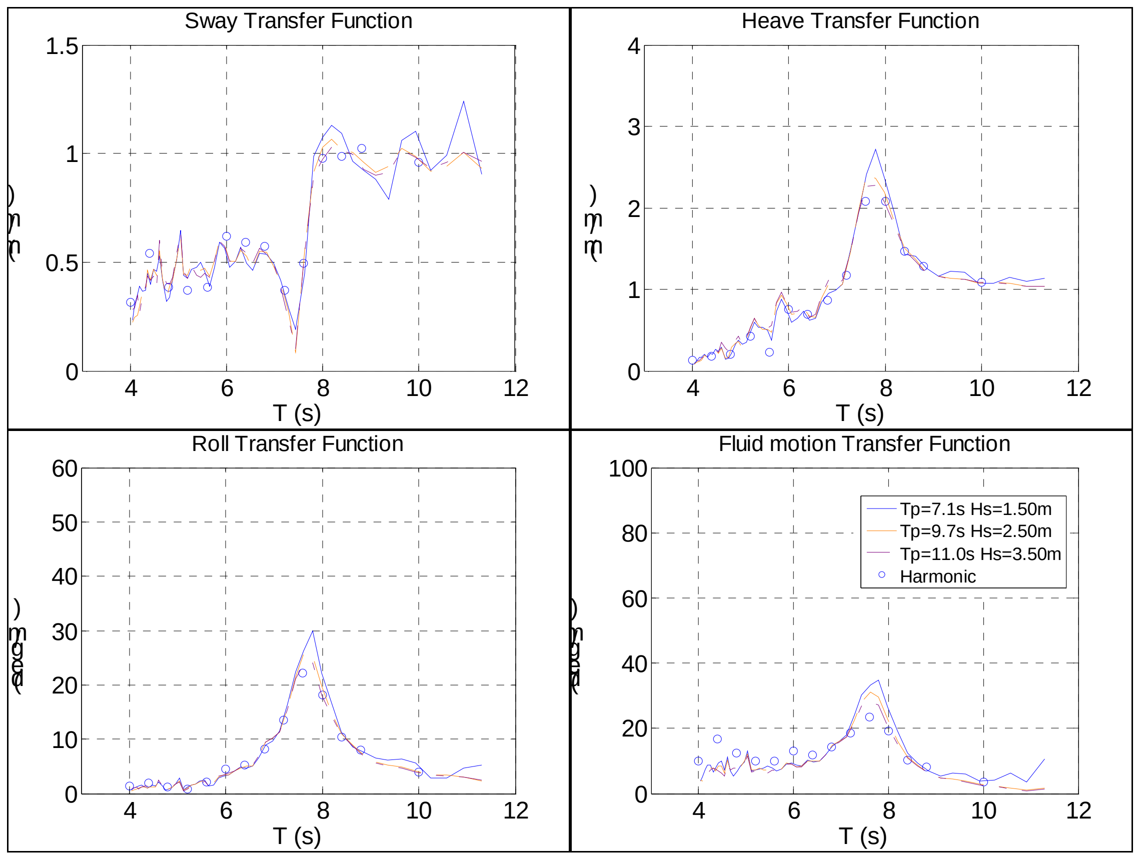


Figure 10 Transfer function amplitudes obtained from regular waves and from irregular waves. Fluid motion damping factor of 0.060.

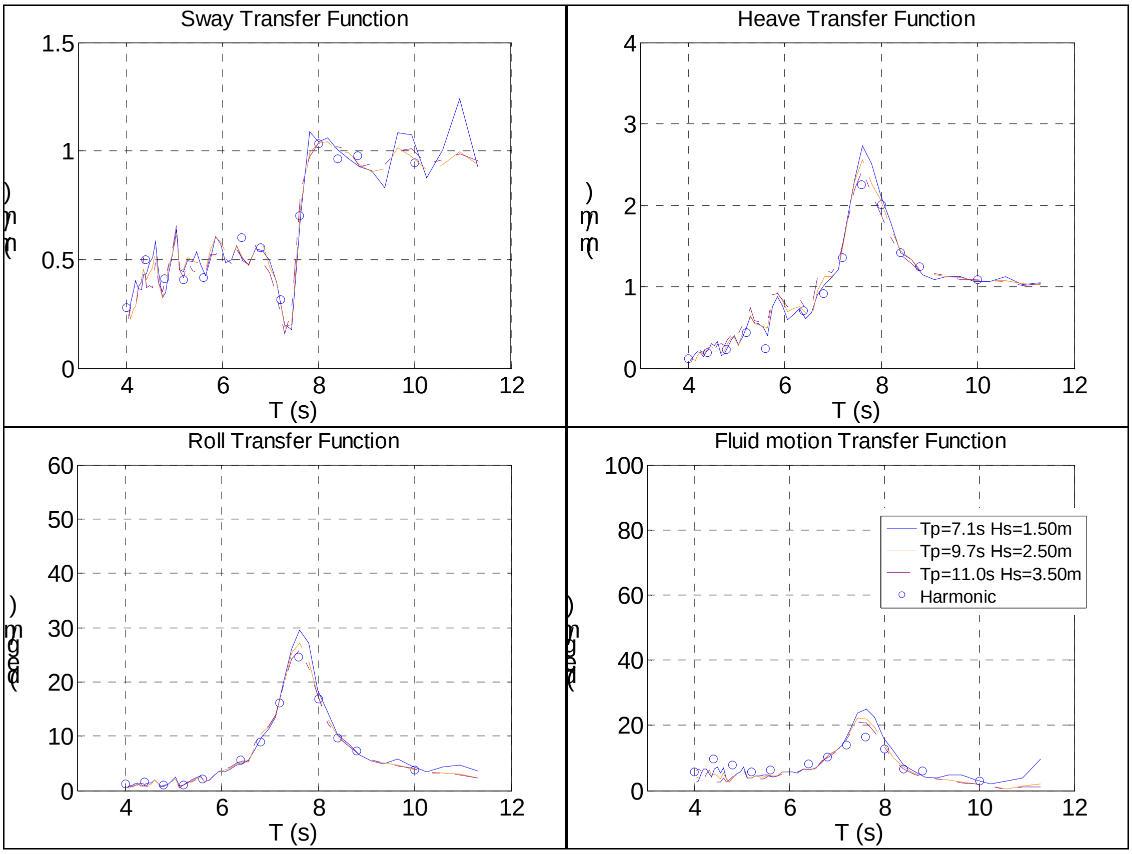


Figure 11 Transfer function amplitudes obtained from regular waves and from irregular waves. Fluid motion damping factor of 0.012.

The transfer functions from three seastates are very similar, except around the dynamic amplification related to the roll natural period (~ 7.8s) where we observe a decrease of the transfer function peak as the significant wave height increases. This is a nonlinear effect as already identified in the previous Section.

The reduction of the transfer functions peaks with the increasing damping of the tank is evident also from the irregular waves results. Finally, one observes an excellent agreement between the regular wave and irregular wave results, except for the peaks related to the rolling resonance where the irregular wave results seem to be slightly larger. Part of the discrepancy can be explained by the fact that, apparently, no regular waves with exactly the rolling natural period were run. The forced roll motion in regular waves may also experience more damping than roll motion in irregular sea state where the exciting energy around the natural period is lower.

## 6 Comparisons between experimental data and numerical predictions

This section presents the comparison between the experimental data obtained with the experimental program and the numerical predictions. The numerical method described in Section 3 is named here as “Lloyd”, since the U-tank dynamics is represented by the model proposed by Lloyd (1989), although in fact it is based on the work of Stigter (1966). The advantage of this method, besides being relatively simple, is that the tank dynamics is represented by an additional equation of motion which is coupled to the rigid body motions of the floater. It is possible in this way to include the power take off effects in the equation of motion by a suitable combination of a spring force and damping force. In the present formulation, we use a linearized damping model to represent the conversion of wave energy.

Section 3 explains that the three dimensional panel method known as Wamit is used to calculate the floater's hydrodynamic coefficients and wave exciting forces. Then these coefficients are combined with the remaining coefficients in the equations of motion to be solved. In fact Wamit works also with internal tanks partially filled with water and this functionality is used to verify the Lloyd's model results. The Wamit internal tanks option cannot be used to represent the WEC because the power take off unit cannot be numerically modeled. The water in the tank is free to move, almost without damping since only free surface effects are considered for the dissipation of energy, and it is not possible to restrain the motion of the water column. This means that one cannot "remove" energy from the motions of the water column. Additionally, the motions of the internal free surface are not known. Anyway, this functionality of Wamit is used to compare with the dynamics predicted Llyod's model without tank damping.

Figure 12 presents the transfer functions amplitudes of the sway, heave, roll and tank motions. Three sets of symbols with different colors correspond to experimental data for the three settings of the tank damping referred before. The experimental data represent averaged results from the tests in different seastates. The numerical results are represented by the lines with different colors for different damping factors of the tank. Continuous lines are used for the Lloyd's method while dashed lines stand for the Wamit results of motions. There is only one line for Wamit, which correspond to the potential flow damping of the tank.

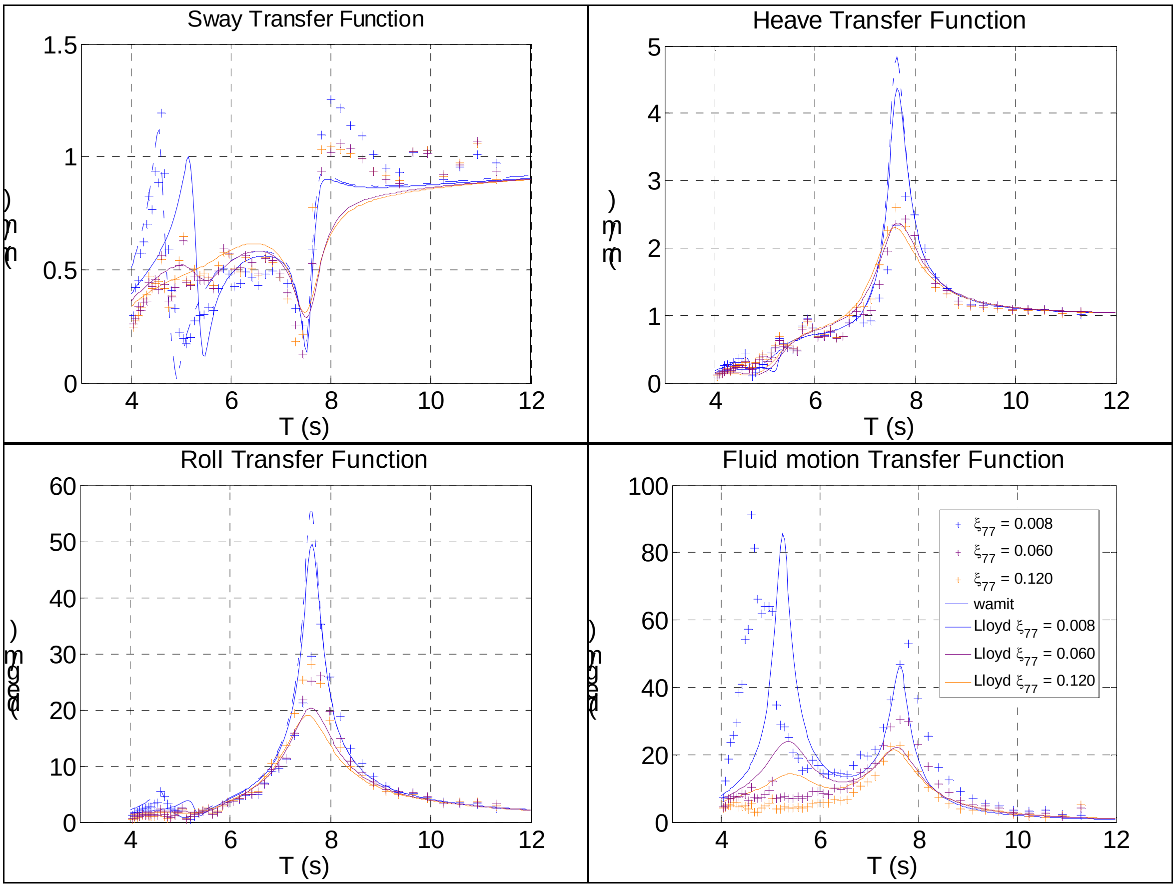


Figure 12 Comparison between experimental and numerical transfer function amplitudes. Three damping factors of the fluid motion in the tank considered.

Starting with the rolling motion, the numerical results agree well with the experimental ones, except for the resonance peak. The numerical results overestimate the experimental peak for the smaller tank damping ($\xi = 0.008$) and they underestimate the peaks for the two larger tank damping. The numerical model reduces much the rolling motion peak with the increase of the tank damping. This effect is not observed in the experimental data, which means that the numerical model does not represent correctly the physical problem in this aspect. There is a small experimental peak at around 4.8s, which is related to the coupling with the motion of water in the tank. Wamit represents very well this peak for the small tank damping condition.

The transfer function of the fluid motion in the tank presents two large peaks, when the tank damping is the smallest. The first is related to the tank natural period (~ 4.8s) and the second with the roll natural period (~ 7.8). The numerical model, with Lloyd's method for the tank dynamics, compares relatively well with the experimental data in terms of amplitudes and frequency range for the second peak, however it predicts a natural period of the tank longer than the experimental one. The numerical discrepancy is related to the simplifications assumed for the model of the tank dynamics. When the tank damping increases there is a very large decrease of the tank motions around the first peak and in this case the numerical results are larger than the experiments. There are no Wamit results for the motions of the water in the tank.

The sway motion is strongly coupled with the fluid in the tank motions and with the roll motion. Wamit predicts very well the first peak of the transfer function (for $\xi = 0.008$), which is related with the tank natural period. This indicates that Wamit is able to represent correctly tank dynamics without damping. The Lloyd's first peak is shifted to the longer periods because the tank natural period is over predicted. Around the rolling natural period, especially on the right side (longer periods), all numerical results underestimate the experimental results. The reason is not clear, however sway and heave are strongly coupled therefore we observe a similar behavior for the heave.

The heave motion is very well predicted for the lighter tank damping, however we observe, again, an exaggerated effect of the tank damping in the peak of the transfer function, since for the two larger damping the numerical peaks are clearly smaller than the experimental ones. The tank damping has almost no effect on the experimental heave peak.

# 7 Prediction of absorbed power

The measurement of converted wave power, or absorbed wave power, is a difficult task at the model scale and therefore was not in the scope of this experimental program. However it is possible to make an estimative with the numerical model presented in Section 3. The wave power is extracted via the relative motion between the oscillating water column and the U tank. The relative angular motion is:

$$\theta(t) = x_7(t) - x_4(t) \tag{11}$$

Assuming that the power take off system (PTO) can be represented by a simple linear damper, then the absorbed power is:

$$P(t) = M_{pto}\dot{\theta}(t) = B_{pto}\left[\dot{\theta}(t)\right]^2 \tag{12}$$

where $B_{pto}$ represents the linearized damping coefficient of the PTO.

In harmonic incident waves equation 12 is equivalent to:

$$P(t) = B_{pto}\{\omega\theta_a \cos(\omega t)\}^2 \tag{13}$$

where $\theta_a$ is the amplitude of the relative motion and $\omega$ is the wave frequency. Time integration over one wave cycle, divided by the wave period, results on the mean power absorbed in harmonic waves:

$$\overline{P} = \frac{B_{pto}(\omega\theta_a)^2}{2} \tag{14}$$

The left figure 13 presents the mean wave power absorbed in harmonic waves as function of the wave period. The power is normalized by the wave amplitude squared. Different lines correspond to different settings of the PTO, meaning different damping coefficients. The damping factors of 0.008, 0.060 and 0.120 were measured during the experimental tests. The red line stands for the power extracted with the optimum setting of the PTO damping, which is frequency dependent, and the black line represents the mean wave power for a wave front with the same width as the WEC (15m).

The red line in the graph shows three peaks for the extracted power distributed between 4 and 8 seconds of wave period. This means that the device has a good potential to work efficiently in multi-frequency seastates (realistic seastates). The first peak is related to the natural frequency of the water in the tank, the second is associated to the heave natural period (although this period is not observed in the heave transfer function) and the third to the rolling natural period. The range of interesting wave periods can be easily adjusted by changing the amount of water in the U-tank. Increasing the amount of water will increase the tank and rolling natural periods. It is therefore possible to tune the dynamic characteristics of the device to the mean period of the incoming seastate.

The right graph of figure 13 shows the damping factor of the PTO corresponding to the maximum power extraction. One observes very large variations along the wave period range, which indicates that an efficient control of the PTO is necessary to use the full potential of the system.

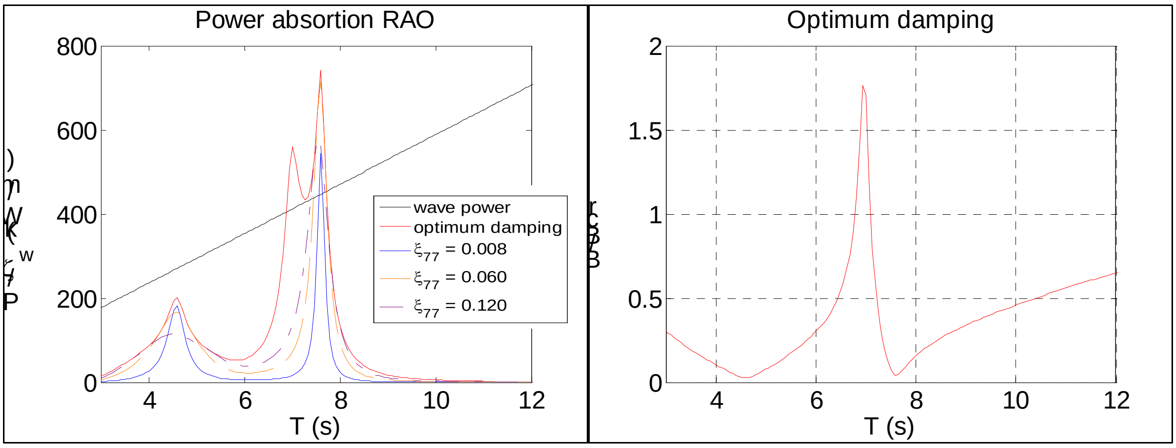


Figure 13 Numerical transfer function of the wave power absorbed from the waves (left graph). Three damping factors of the fluid motion in the tank considered, together with the results corresponding to the optimum damping factor. Optimum damping factor (right graph).

## 8 Conclusions

This paper presents the motion results from an experimental program in regular and irregular waves with a scaled model of a wave energy converter. The objective was to obtain insight into the dynamics of the device and also obtain experimental data to assess the validity of a numerical model to represent the hydrodynamic wave-body interactions. The concept is based on a floating body with an internal U tank partially filled with water. The sway, heave and roll oscillations force the motion of the water in the tank and the energy is extracted from this motion.

The experimental results show two distinct frequency ranges with large dynamic amplification of the fluid motion in the tank. The first is related to the natural period of the oscillating water column it self and the second one occurs around the rolling motion natural period. The two peaks of the tank transfer function are beneficial in irregular waves since they widen the frequency range where the wave energy is captured. The sway motion is strongly coupled to the tank motion and there is also a small coupling between the tank motion and heave and roll. Both the sway and heave are coupled to rolling motion. For these reasons UGEN has the potential to extract the wave energy from three modes of rigid body motions.

Increasing the damping of the power take off system (PTO) decreases very much the oscillations of the water in the tank and there is a small decrease of the roll and heave transfer function peaks. The transfer functions obtained from irregular wave tests compare very well with the ones from regular wave tests which shows consistency in the experimental data.

Several conclusions are taken from the comparison between experimental motion responses and numerical predictions. Firstly, we conclude that the Wamit model with internal tanks is able to predict very well the coupling effects of the tank motions into the sway, heave and roll motions. However Wamit does not calculate the free sueface elevation in the tank and it is not possible to simulate the extraction of energy from the tank motions. Regarding the simplified Lloyd model to represent the dynamics of the tank, it overestimates the natural period of the tank (1.31s compared to 1.23s), which is reflected on the transfer function of the tank motions and also on the coupling with the rigid body motions.

The numerical predictions underestimate the sway motions between 8s and 9s of wave period. The increase of the tank damping reduces the rolling resonance peak, however this effect is overestimated by the numerical model. For these reasons, we conclude that the numerical model of the WEC dynamics needs to be improved.

The mean power extracted in regular waves, estimated by the numerical model, shows three peaks distributed between 4 and 8 seconds of wave period. This means that the device has a good potential to work efficiently in multi-frequency seastates (realistic seastates). The peaks are related to the natural periods of the tank, heave and roll motions.

## 9 Acknowledgments

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