NUMERICAL MODELLING AND ASSESSMENT OF THE UGEN FLOATING WAVE ENERGY CONVERTER

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SUMMARY

The paper presents a linear hydrodynamic model for the UGEN wave energy converter, an analysis of the dynamics of the system and the predicted ability to extract energy from the waves. 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 between the water inside the tank and the rolling of the floater. 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.

NOMENCLATURE

$\tilde{n}_{tk}$	Generalized unit normal vector pointing out of the tank surface ([m])
$\overline{P}$	Average absorbed Power (W)
A_{ij}	Added mass (Ns^2m^{-1} or Ns^2m^{-2} or Ns^2m^{-3})
B_{ij}	Damping coefficients (Nsm^{-1} or Nsm^{-2} or Nsm^{-3})
B_c	Critical damping for fluid rotation (Nsm^{-3})
B_{PTO}	PTO damping (Nsm^{-3})
C_{ij}	Restoring coefficients (Nm^{-1} or $Nmrad^{-1}$)
F_k^E	Wave exciting forces (N or Nm)
F_{tk}	Forces associated to fluid motion inside the tank (N or Nm)
G	Centre of gravity
I_{kj}	Inertial moments (kgm^2)
L_t	Length of tank (m)
M	Total mass (kg)
M_{PTO}	Moment exerted by the PTO (Nm)
O	Origin of the coordinate system
P	Absorbed Power (W)
PTO	Power takeoff system
P_{tk}	Linear hydrodynamic pressure inside the tank (Nm^{-2})
S_{tk}	Tank surface (m^2)
T_N	Uncoupled natural period of the tank (s)
X_G	Longitudinal centre of gravity (m)
Y_G	Transversal centre of gravity (m)
Z_G	Vertical centre of gravity (m)
Z_{tk}	Vertical position of tank free surface (m)
g	Gravitational acceleration (ms^{-2})
h_d	Height of the tank conduct (m)
h_r	Height from the centre of tank conduct to O (m)
q	Friction coefficient on tank surface
r_d	Radius from G to the centre of conduct (m)
w_d	Width of the tank conduct (m)
w_r	Width of the tank reservoirs (m)
x_j	Motions on the 7 degrees of freedom (m or rad)
w_d	Width of the tank conduct (m)
ϕ^{Rtk}	Radiation velocity potential in the tank
ϕ_j^{Rtk}	Radiation velocity potential in the tank for an unit amplitude motion in the j^{th} mode
Θ	Relative motion (rad)
Θ_a	Amplitude of the relative motion (rad)
δ_h	Vertical motion of the water inside the tank (m)
ρ	Density of water ($kg\ m^{-3}$)
ω	Wave frequency (rad/s)
ξ_{77}	Fluid motion damping factor

1 INTRODUCTION

The wave energy results from the transfer of energy from the wind to the sea surface, while the wind is generated by the solar irradiation. For these reason the wave energy can be seen as a concentrated form of solar energy. Compared to the solar and wind energy, the wave energy on a favorable ocean site has the advantages of higher energy density and being more constant over time. In spite of the known potential and the research and development effort over the last decades, the conversion and utilization of this potential at reasonable costs is still a big scientific and technical challenge.

Many concepts of Wave Energy Converters (WECs) have been proposed, investigated, some of them developed to the prototype 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 [1] and Nielsen et al. [2,3].

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 a new concept of a floating wave energy converter named as UGEN (floating device with a U tank for GENeration of electricity from waves). 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 and these oscillations are excited mainly by the rolling of the floater. However the roll motion is coupled with the sway and heave motions therefore the system has the potential to extract energy from three modes of rigid body motions. One of the advantages of this concept is that the floater is completely closed from the exterior and it has no moving parts or articulations, thus it is a robust system.

The paper presents a linear hydrodynamic model for the wave induced motions and power extraction from the waves. This linear model is used to analyse the system dynamics and of device performance in waves. The wave/body interactions are calculated with a frequency domain Green function panel method, while oscillatory motions of the U shaped water column are represented by an additional degree of freedom coupled to the rigid body modes of motion. The hydrodynamic coefficients associated to this degree of freedom are derived from a simplified method based on the one-dimensional Euler equation.

2 THE UGEN CONCEPT

The UGEN 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 with respect to the rolling of the floater. Figure 1 shows a perspective view of the wave energy converter, while Figure 2 presents a side view illustrating the main components 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 a reversible turbine inside. 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.

The dimensions presented in figure 1 and the main characteristics of the device in Table 1 result from a design for operation in the west coast of Portugal where the mean wave period is around 7.5 seconds. The uncoupled roll natural period is 7.3 seconds, although the coupled natural period is slightly larger, as will be presented in Section 5. This device has a displacement of 1153 tons, of which 42% is the mass of the oscillating water column. The width of the front side facing the incident waves is 15m while the length is 20m and the maximum draft is 5m.

The UGEN is characterized by two important natural periods, the rolling natural period and the oscillating water column natural period. If these two periods coincide, then the tank works as a roll stabilizing device. It is advantageous to separate the two natural periods, which means to reduce the period of the tank with respect to the roll natural period. The ideal separation interval requires an investigation. In the present case the natural period of the tank is 5.4 seconds.

Table 1: Characteristics of the wave energy converter

Length (m)	20.0
Width (m)	15.0
Depth (m)	10.0
Draft (m)	5.0
Mass total (ton.)	1153
Mass in U Tank (ton.)	490
Roll inertia (ton*m^2)	6.64e4
ZG(m) from base line	5.0
Roll uncoupled natural period (s)	7.28
Tank uncoupled natural period (s)	5.44

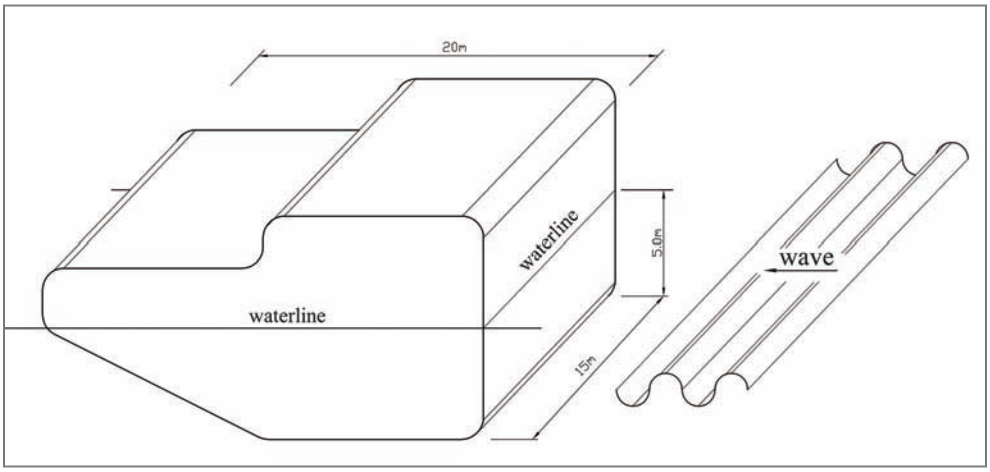

Figure 1: Perspective view of the UGEN wave energy converter

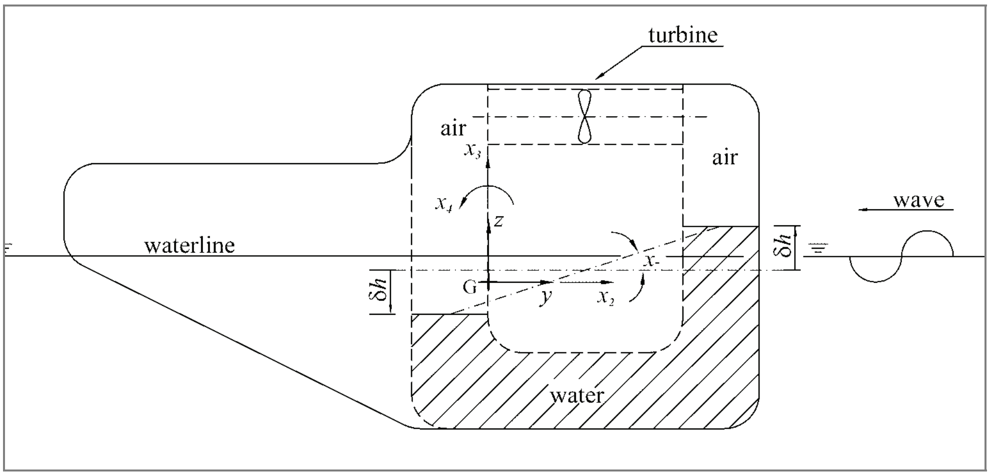

Figure 2: Side view of the UGEN wave energy converter, coordinate system and convention for the motions

3 NUMERICAL MODEL

3.1 PANEL METHOD FOR WAVE BODY INTERACTIONS

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, δh, is represented by and additional rotational degree of freedom x_7 as represented in figure 2.

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 [4] and Lee [5]. 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).

3.2 HYDROMECHANICS OF THE U TANK

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 [6] for the oscillations of U tube passive tanks to stabilize ship motions. A simplification of this theory is presented by Lloyd [7], which is the method applied here.

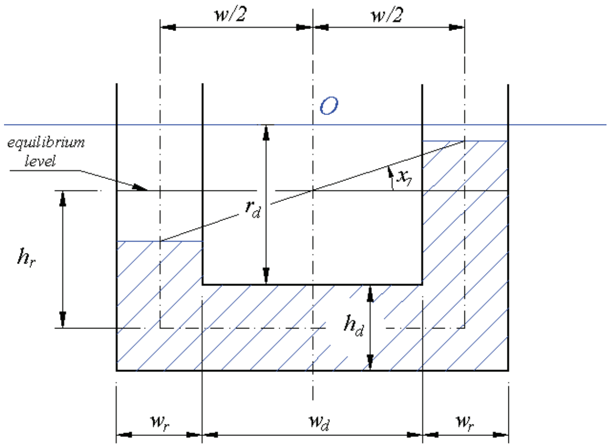

Figure 3: Passive U tank of Lloyd's (1989) method

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 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:

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

The hydrodynamic coefficients are:

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

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

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

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

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

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

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

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

where q, g and ρ 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.

3.3 EQUATIONS OF MOTIONS

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:

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

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.

This numerical model assumes that the effects of the power take off system can be represented in the equations of motion by a linear damping coefficient multiplied by the relative motions between the oscillating water column and the tank. The pressure distribution in the interior free surface is neglected, as well as any wave effects, therefore it is like the air is pushed by a weightless piston. This assumption is believed to be adequate since the area of the interior free surface is small compared to the water column vertical motions.

The other assumption is the incompressibility of the air. Some authors have investigated the oscillating water column concept to convert energy from the waves based on the assumption that the air compressibility is small, as for example Evans [8]. However the most recent numerical models include the effects of compressibility in order to obtain accurate results [9, 10]. The compressibility of the air introduces a spring effect which increases with the height of the air reservoir.

Regarding the model presented here, which assumes incompressibility, it is believed that the results are qualitatively correct and accurate enough to take general conclusions regarding the concept.

Finally it is assumed that the turbine characteristics are liner, which is a valid approximation for the reversible Wells turbine, if the pressure head is not high (Falcão and Rodrigues [11].

3.4 MEAN ABSORBED WAVE POWER

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

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

As explained in the previous Section, this model assumes that the turbine is linear, the air flow is incompressible and the interior free surface is flat.

4 VALIDATION OF THE U-TANK HYDRODYNAMIC MODEL

The hydrodynamic model to represent the motions of the water in the tank and the couplings with the rigid body modes of motion is based on several simplifying assumptions. This Section discusses the validity of the method by comparing the motion responses with the Wamit results with internal tanks. In fact Wamit includes an option to consider internal tanks partially filled with water and the solution is consistent with the 3D linear formulation for the body/wave interactions, therefore all effects up to the first order are included.

Wamit formulates the fluid in the tank hydrodynamic problem in a similar manner as for the exterior domain wave/body interactions. The velocity potential includes only the radiation component since there is no incident and scattering potentials:

$$\Phi^{R_{TK}} = \sum_{j=1}^{6} \xi_j^a \phi_j^{R_{TK}} \tag{15}$$

where ξ_j^a is the amplitude of the harmonic motion in the *j* mode and $\phi_j^{R_{TK}}$ is the radiation potential in the tank for an unit amplitude motion in the same mode. The velocity potential in the tank must comply with the Laplace equation and boundary conditions similar to those of the exterior fluid problem. The numerical solution for the potential is obtained simultaneously for the two fluid domains and a condition is necessary to impose no influence between the separated fluids. Once the potential is known, the linear hydrodynamic pressure results from the application of the linearized Bernoulli's equation:

$$p_{tk} = -\rho\frac{\partial\Phi^{R_{TK}}}{\partial t} - \rho g\left(z - Z_{tk} + x_3 + x_4 y - x_5 x\right) \tag{16}$$

where *x*, *y*, *z* are the coordinates of a point on the tank surface, Z_{tk} is the vertical position of the tank free surface with respect to the origin of the coordinate system and x_j, *j* = *3*, *4*, *5* are the vertical rigid body motions.

Integration of the pressure over the tank mean wetted surface, weighted by the generalized unit normal vector pointing out of the tank, $\tilde{n}_{tk}$, results on the forces associated to the motions of the fluid in the tank:

$$F_{tk} = \iint_{S_{TK}} p_{tk}\tilde{n}_{tk}\,dS \tag{17}$$

The result include tank hydrostatic forces, represented by coefficients which are summed to the floating body hydrostatic matrix, and tank inertial forces represented by added mass coefficients. Since there are no free surface waves radiated away from the tank, the damping forces are negligible.

The Wamit with internal tanks results are appropriate to compare and assess the Lloyd's method, assuming the condition of zero tank damping. On the other hand it cannot be used to represent the dynamics of the wave energy converter, without modification of the source code, because the power take off unit cannot be numerically modeled. In fact it is not possible to restrain the motion of the U water column, meaning that it is not possible to extract energy from the motions of the water column.

Figure 4 presents the motion transfer function amplitudes, namely of the sway, heave, roll and fluid motion in the tank, as function of the harmonic wave period. All amplitudes are normalized by the incident wave amplitude. The dashed blue line represents the results from the method proposed here (Lloyd´s tank) and the red line represents the Wamit with internal tank results (Wamit tank). The motion of the fluid in the tank has no damping. Furthermore, no viscous damping is used for the other modes of motion, therefore the resonance peak of the roll motion is unrealistically large.

One observes a perfect agreement of the two numerical models for heave and pitch, except for the wave period range around 5 seconds however the magnitude of the motions are almost negligible here. The lower right graph presents the fluid motion in the tank predicted by the Lloyd's method (Wamit does not provide the free surface elevation inside the tank), which is characterized by two large peaks. The first one is related to the tank natural period (occurs at 5.2s) and the second is related to the rolling natural period (occurs at 7.7s).

Regarding the sway motion, the agreement is very good above 6 seconds of period, but not good around the 5 seconds period. The dynamic amplification observed around the 5 seconds period is due to the coupling with the fluid in the tank motion. In fact the Llyod's method over predicts the natural period of the water in the tank and for this reason the first peak of the sway motion occurs at 5.2s while the Wamit peak occurs at 4.8s. The uncoupled natural period of the tank can be calculated using the inertia and restoring coefficients of the fourth equation 10:

$$T_n = 2\pi\sqrt{\frac{A_{77}}{C_{77}}} = 2\pi\sqrt{\frac{w_r w + 2h_r h_d}{2gh_d}} \qquad (18)$$

The result of the uncoupled tank natural period according to the simplified method is 5.44s. Numerical predictions of the water column free oscillations with a two dimensional potential flow code results on a first natural period of 5.00s.

The comparisons lead to the conclusion that the Lloyd's method slightly over predicts the natural period of the tank. However, above the 6 seconds wave period this simplified method seems to represent very well the coupled dynamics of the floater with a large internal U tank partially filled with water. In fact this limitation of the method for the period range around 5 seconds is not a problem because the interesting period range in realistic seastates is above 6 seconds.

One concludes that the simplified model is adequate, at least, for qualitative assessment of the wave energy converter proposed here.

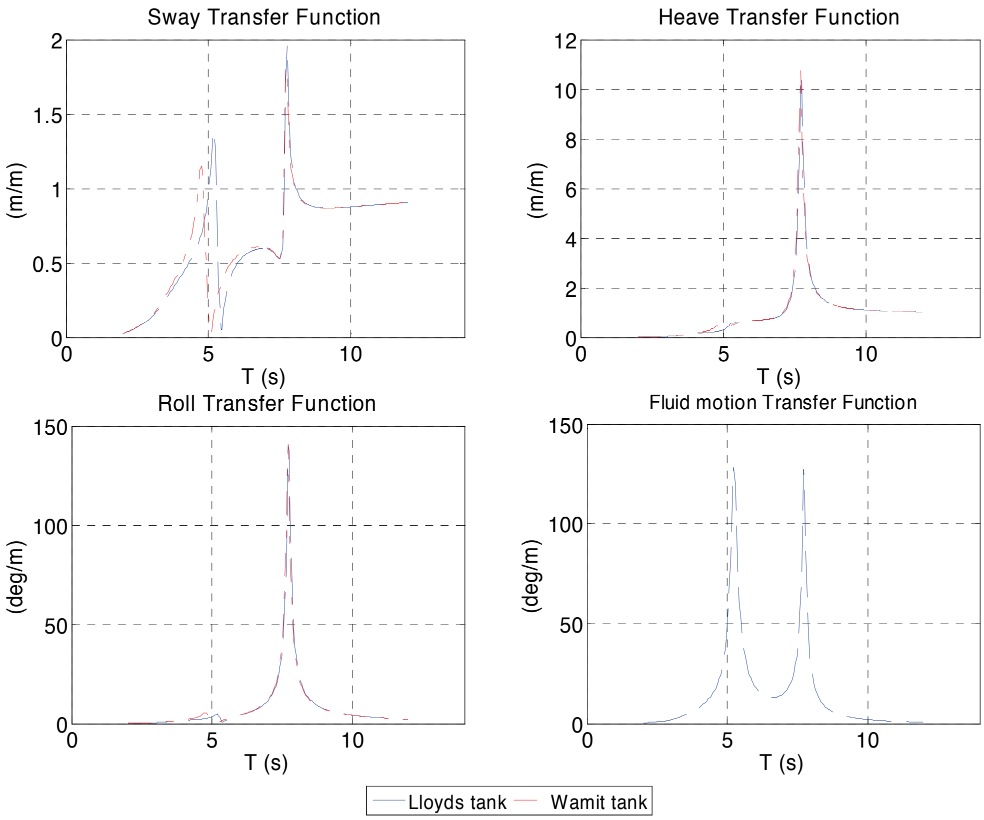

Figure 4: Transfer function amplitudes of the rigid body motions and fluid in the tank motions.

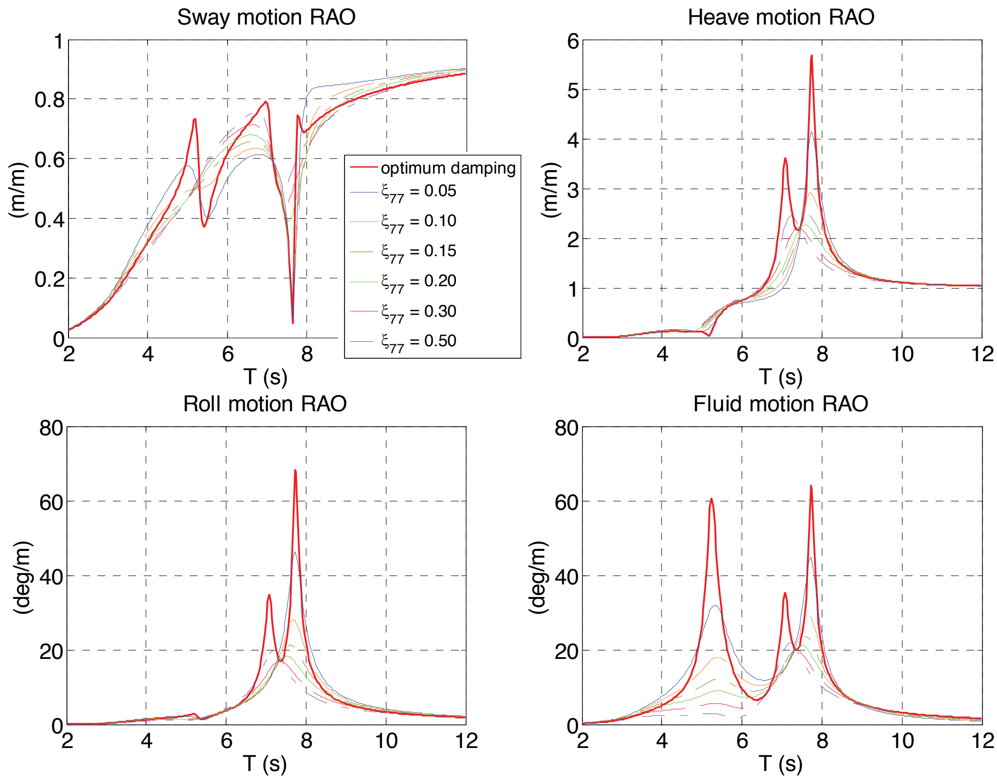

Figure 5: Transfer function amplitudes as function of the PTO setting (Bpto).

5 ANALYSIS OF UGEN PERFORMANCE IN WAVES

This section presents an analysis of the dynamic behavior in waves of the UGEN and of the ability of the system to extract energy from the waves. The power take of system (PTO), which will in the future be based on a reversible turbine, is represented here in a simplistic way by the numerical model. The conversion of energy is represented by a linear damper that is actuated by the relative motion of the water inside the tank. The graphs of figure 5 present the motion transfer function amplitudes for various settings of the PTO, meaning various damping coefficients of the linear damper. The corresponding damping factors, $\xi_{77} = B_{pto} / B_c$, are presented in the legend of the graphs and the critical damping is defined as $B_c = 2\sqrt{C_{77} A_{77}}$. The red thick line represents the results for the optimum damping coefficient in terms of wave energy extraction.

One observes a clear reduction of the dynamic amplification peaks related to the natural periods of roll and tank motions as the tank damping increases. This is especially noticeable for the tank motions around the tank natural period where there is no dynamic amplification for a damping factor larger then 30%. Interestingly one observes a shift of the roll dynamic amplification for the lower periods and the tank damping increases. The roll dynamic amplification decreases up to a damping factor of around 20% and then it increases again for larger tank damping. The heave transfer function has a similar behavior because it is strongly coupled with the roll motion.

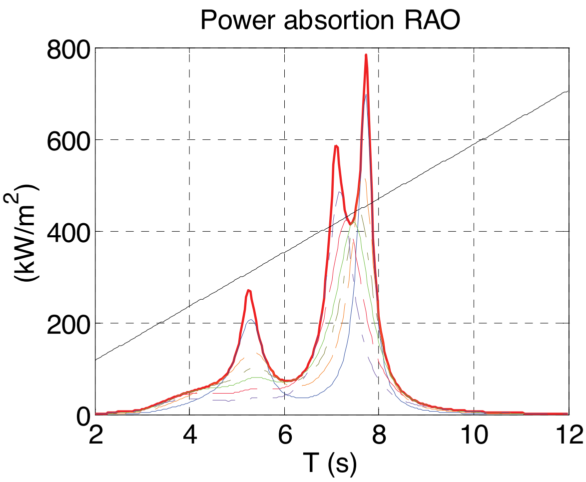

Figure 6: Transfer function of the absorbed wave power for various settings of the PTO (Bpto).

Figure 6 presents the transfer function of the mean wave power absorbed as function of the wave period. The results, in kW, are normalized by the wave amplitude squared. Different lines stand for different settings of the PTO, meaning different damping coefficients, and the red line corresponds to the optimum damping coefficient.

The black line represents the mean wave power contained on a wave front with a width equal to the wave energy converter width (15m). The system has the potential to work with a capture width larger than one for wave periods between 7 and 8 seconds. In figure 7 one observes the distribution of optimum damping coefficient of the tank as function of the wave period. The coefficient is normalized by the critical damping. The graph shows a very large variation of the damping coefficient which optimizes the energy extraction, which indicates that the power take off system must be coupled to an efficient control system.

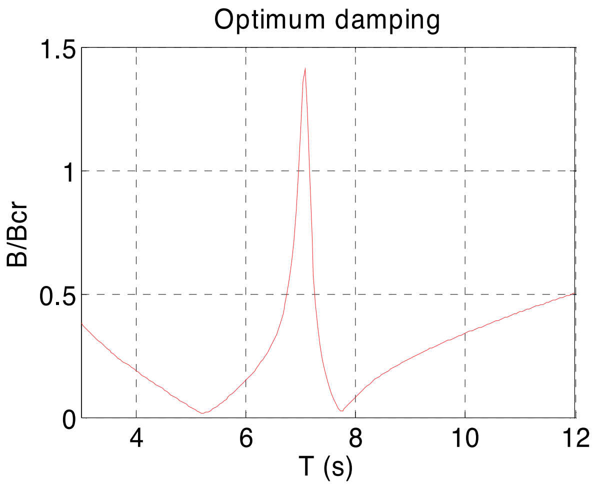

Figure 7: Optimum damping of the PTO

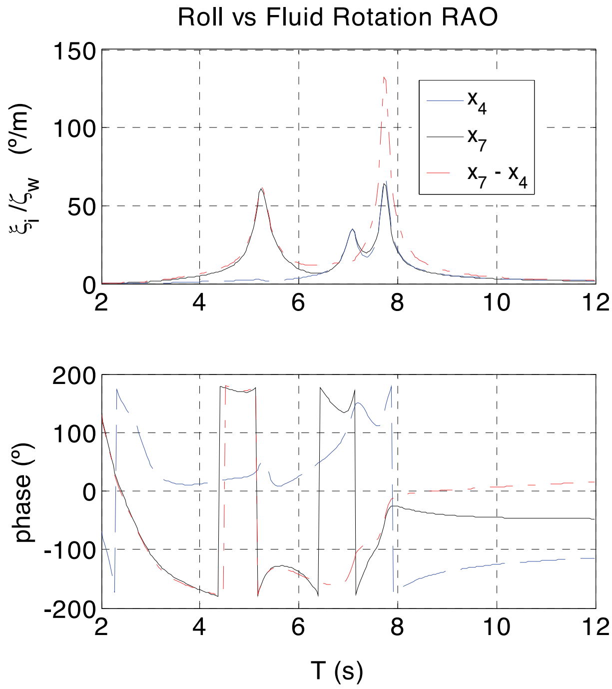

Figure 8: Amplitudes and phases angles of the roll and fluid motions (Bpto/Bc = 0.05)

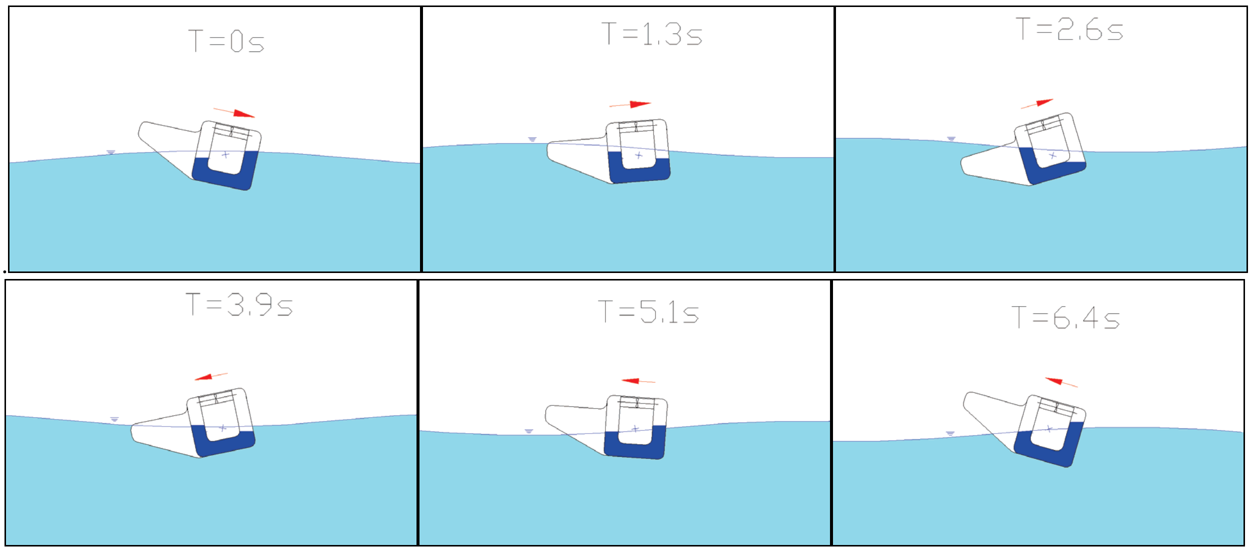

Figure 9: Time sequence of the rigid body motions and fluid motions in harmonic waves with the rolling natural period (T = 7.7s).

It is interesting to investigate the phasing of the water in the tank motions with respect to the forcing motion. Figure 8 presents the transfer function amplitudes (upper graph) and phase angles (lower graph) of the roll motion (blue line), tank motion (black line) and relative angular motion between the fluid and the tank (red line). The damping coefficient of the tank corresponds to 5% of the critical damping. The relative motion is largest around 7.5 seconds which coincides with the rolling resonance and also with the peak of the power extraction. For this condition the delay between the tank motions and the roll motion is large, around 120º, which means that the two motions move in opposite directions most of the time. The dynamics around the lower period peak is different from the former. In this case the rolling motion is very small, because the wave exciting period is well bellow the roll natural period. However, the U tank water column has very large motions because it is excited at the natural period.

Figure 9 shows a time sequence of the rigid body motions and fluid motions in harmonic waves with the period of 7.7s. The damping of the tank is set at 5% o the critical damping. The wave elevation is scaled up so that the phasing of the wave relative to the rolling and tank motions is easy to observe. The red arrow above the floater indicates the direction of the air flow at that instant. Since the air is assumed incompressible, the direction of the air flow is the same as the direction of the relative motion between the water column and the tank (x_7 - x_4). The sequence shows that in fact the rolling motion in approximately in opposite phase with respect to the tank motion.

6 CONCLUSIONS

This paper presents a new concept of a wave energy converter, the UGEN, which consists of a floater with an internal U tank partially filled with water. The amount of water accounts for around 40% of the total displacement. The wave energy is extracted from the oscillatory motions of the U shaped water column. A linear hydrodynamic model was implemented to calculate the device performance in waves, where the oscillating water column effects are represented by a simplified method.

The system is characterized by two important natural periods, the rolling and the U tank natural periods. It was concluded that the system performs better if the two natural periods are separated, which means to reduce the period of the tank with respect to the roll natural period. In the present case, the uncoupled natural periods are 5.4s and 7.3s for the tank and roll motions.

The simplified model for the oscillations of the U shaped water column slightly overestimates the natural period of the tank, which affects mainly the sway motion and the prediction of power absorption around this natural period. The magnitudes of these responses are correct (within the linear approach) but slightly shift in the period range. The hydrodynamic model gives (linear) correct results for the period range where the device extracts more energy from the waves, meaning around the rolling natural period.

The predicted transfer function of mean power extracted from the harmonic waves shows a capture width larger than one around the rolling natural period. However the frequency band is narrow, therefore it is important to use an efficient control of the power take off. The optimum linear damping of the PTO varies much along the period range.

The linear hydrodynamic model assumes that the air flow is incompressible, while in fact the compressibility induces a spring like effect. The related effects are not negligible if the height of the air chambers is large and this aspect needs to be investigated.

7 ACKNOWLEDGEMENTS

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