Modelling of hydraulic performance and wave energy extraction by a point absorber in heave

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Abstract

The feasibility of energy extraction from sea waves has been investigated, with special attention to potential applications in the Belgian coastal area of the North Sea. The performance of heaving point absorbers in wave conditions that are representative for the considered area is calculated by means of a linear theory. The geometry of the heaving buoy, the external damping and a supplementary inertia are considered as variable parameters to optimise the absorption system. Further, the numerical results are validated by means of physical model testing.

The resulting power absorption performance appears to be wave height dependent. For regular waves of relatively small amplitude the absorption length significantly exceeds the absorber diameter and diminishes with larger wave heights. In irregular waves, the absorption length is estimated to reach 60% of the buoy diameter. The comparison between experimental and numerical data shows discrepancies that are primarily related to two issues that inversely affect the absorber effectiveness. Firstly, significant vortex shedding and viscous losses occurring with significant buoy motion reduce the power extraction. Secondly, the actual decrease in absorbed power due to the mistuning effect in irregular waves is smaller as revealed from computational prediction. Regarding the significant motion, restrictions must be included in order to avoid slamming of the buoy. This may be achieved by increasing the external damping compared to the theoretical optimal values or, alternatively, by increasing the draft of the buoy. The adaptation of the draft is also shown as a measure to increase the overall absorber efficiency in natural seaways. In the end, considering the frequency of occurrence of the wave spectra, optimal characteristics for the point absorber are determined. An optimal absorber is evaluated as rated to a 100 kW, with an annual average power capture of about 30 kW or 263 MWh per year per point absorber unit.

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Keywords: Wave energy; Heave; Point absorber

1. Introduction

The oil crisis of the 1970s turned out to be an irreversible stimulant for the scientific investigation and the development of technologies concerning the exploitation of alternative energy sources. For wind and solar energy, this resulted into a breakthrough on a rather limited scale. Although the extraction of energy from sea waves initially appeared to be promising as well and received considerable international interest, most projects did not result into the construction of a prototype, but only reached the level of physical or numerical modelling.

Due to the decrease of oil prices in the 1980s, the general interest in alternative sources of energy vanished. Currently, an increased demand for energy and the need for a dramatic descent of the CO\textsubscript{2}-production, as formulated in the decisions from the 1997 world conference of environment in Kyoto, are stimulating factors for a renewed interest.

World-wide a number of projects is dealing with technology development that could be successfully deployed in seas to harness the wave energy, based on different operational concepts. One can distinguish two major categories of wave energy converters: active devices where the interface element responds to the wave action and produces the mechanical work, and passive devices where the device remains stationary and the water
Nomenclature

\[ a \] added mass (kg)
\[ A_w \] waterline surface, \( = \pi r^2 \) (m²)
\[ b \] hydrodynamic damping (kg/s)
\[ b_{\text{ext}} \] external damping (kg/s)
\[ c \] hydrostatic restoring coefficient, \( = \rho g A_w \) (kg/s²)
\[ F \] vertical exciting wave force (N)
\[ F_d \] damping force (N)
\[ d \] draft of buoy (m)
\[ g \] gravity acceleration (m/s²)
\[ H_s \] significant wave height (m)
\[ m \] buoy mass, \( = \rho V \) (kg)
\[ m_{\text{sup}} \] supplementary mass (kg)
\[ N_{\text{KC}} \] Keulegan–Carpenter number-
\[ r \] radius of buoy waterline (m)
\[ t \] time (s)
\[ T \] average apparent wave periods
\[ T_{n0} \] natural period of buoy for heave motion at \( m_{\text{sup}} = 0 \) (s)
\[ V \] buoy displacement volume (m³)
\[ z \] vertical position of buoy (m)
\[ z_{AS} \] significant heave amplitude (m)
\[ z_t \] vertical position of buoy relative to free surface (m)
\[ z_{\text{AS},\text{max}} \] maximum allowable significant amplitude of \( z_t \)
\[ \alpha \] edge radius (m)
\[ \lambda \] wave length (m)
\[ \lambda_p \] power absorption length (m)
\[ \omega \] wave angular frequency (s⁻¹)
\[ \omega_n \] natural frequency of buoy for heave motion (s⁻¹)
\[ \delta \] relative displacement amplitude between the edge and a typical water particle in its vicinity (m)

The present investigation is related to wave energy utilisation based on a point absorber, which is defined as a floating body with dimensions that are small compared to the incident wavelength. The conversion principle, based on the resonant point absorber, received considerable interest in the seventies, as to mention the relevant theoretical works by Evans [5] and extended studies in Norway by Budal and Falnes [6–8]. These pioneer investigators have contributed to the development and practical employment of that kind of absorber. Further, they promoted an idea of wave energy power plants consisting of many relatively small units, in contrast to large-scale converters reaching several megawatts. This idea was supported by reasoning of easier development and cheaper mass production of small absorber units [9]. Moreover, the power capacity of wave energy conversion units is limited due to the relationship between the optimal dimensions of converter units and the dominating wavelength of the incident waves. The wind energy industry, which started with a power capacity of some tens of kilowatts two to three decades ago, now has realised wind-power units of several hundreds of kilowatts, and even into the megawatt range. Even if it is not possible to design single wave absorber units in this power range, a megawatt wave energy plant will always be composed of a large number of smaller wave energy absorbers.

The present paper gives an overview of the different stages of a research project carried out at Ghent University in order to evaluate the feasibility of wave energy conversion in the Belgian coastal area of the North Sea by means of heaving point absorbers. In a first phase, optimal buoy geometry and dimensions were determined by means of numerical calculations based on linear theory, taking account of the local wave climate. Secondly, model tests were executed in order to evaluate the results of the numerical calculations. The available experimental data finally allowed an adaptation of the hydrodynamic design of the point absorber.

2. Evaluation of the capacity

A feasibility study of a wave energy power plant requires detailed hydro-meteo data on the spatial and temporal distribution of the available wave energy in the area of the deployment. Not only the average energy level, but also the distribution in the frequency domain as well as the directional distribution are of importance. Variations of wave characteristics on a yearly basis are also significant.

A study by Truijens [10], who analysed a comprehensive series of registered wave data in order to define the wave climate in the Zeebrugge area, provides a solid database concerning the wave energy potential in front of the Belgian
Average wave spectra are determined in function of following parameters:

- location: 5 wave measuring buoys were considered;
- Nine wind directions were distinguished (N/NE/E/SE/S/ SW/W/NW/indefinite);
- Fifteen significant wave height ($H_s$) classes were taken into account;
- average apparent wave period ($T_z$): 10 classes are distinguished.

For the evaluation of the performance of a particular point absorber design in realistic seas, nine representative spectra, corresponding with the dominant wind direction (SW), were selected (Table 1, Fig. 1).

It should be noticed that about 90% of total available energy is allocated in three $H_s$-classes: 3, 4 and 5. The average energy level is 7–8 kW per meter of incident wave.

### Table 1

Selected spectra: Akkaert Bank (water depth 22 m), wind sector 6 (SW)

<table>
<thead>
<tr>
<th>$H_s$ class</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H_s$ (m)</td>
<td>0.0–0.5</td>
<td>0.5–1.0</td>
<td>1.0–1.5</td>
<td>1.5–2.0</td>
<td>2.0–2.5</td>
<td>2.5–3.0</td>
<td>3.0–3.5</td>
<td>3.5–4.0</td>
<td>4.0–4.5</td>
</tr>
<tr>
<td>$T_z$ (s)</td>
<td>2.5–3.5</td>
<td>3.5–4.5</td>
<td>3.5–4.5</td>
<td>3.5–4.5</td>
<td>4.5–5.5</td>
<td>4.5–5.5</td>
<td>5.5–6.5</td>
<td>5.5–6.5</td>
<td>5.5–6.5</td>
</tr>
<tr>
<td>Occurrence (%)</td>
<td>0.78</td>
<td>1.74</td>
<td>50.43</td>
<td>28.50</td>
<td>13.29</td>
<td>3.63</td>
<td>1.10</td>
<td>0.49</td>
<td>0.02</td>
</tr>
</tbody>
</table>

### 3. Numerical evaluation of converter design—hydrodynamic aspects

#### 3.1. General considerations

The selection of an optimal wave energy converter design requires the comparison between the energy extracted by different converters from representative seas. The wave motion, however, is a stochastic phenomenon, which can be considered as an infinite sum of harmonic components; in general, a wave energy converter will not absorb the energy of each component with the same efficiency. A successful wave absorber for a specific sea condition should fulfil following conditions:

- the frequency for which the converter is most receptive should coincide with the dominant component in the wave spectrum;
- it should be possible to adapt this frequency to variations of the sea state;
- the converter should be able to absorb the energy of other wave components with acceptable efficiency as well;
- if the performance of the absorber depends on the wave direction, these considerations are also valid for the directional distribution.

![Fig. 1. Selected spectra (Akkaert Bank, SW wind direction).](image-url)
3.3. Evaluation criteria

In a linear approach, the heave motion $z$ of the buoy is determined by:

$$
(m + m_{sup} + a) \frac{d^2 z}{dt^2} + (b + b_{ext}) \frac{dz}{dt} + cz = F
$$

(1)

$a$ and $b$ being the added mass and hydrodynamic damping coefficients, $c$ the hydrostatic restoring force coefficient and $F$ the exciting wave force. All parameters depend on the buoy geometry; $a$, $b$ and $F$ are also frequency dependent. $F$, of course, also depends on the wave amplitude.

For a given buoy shape, optimal values for $m_{sup}$ and $b_{ext}$ are determined in function of the waterline radius for each selected spectrum, fulfilling two criteria:

(a) the power absorbed by the external damping system should be maximised;

(b) the probability of slamming due to excessive vertical motions of the buoy relative to the free water surface should be limited to an acceptable value.

In a regular sea with frequency $\omega$ and wavelength $\lambda$, the power absorbed by the external damping system equals the power in the incident wave over a crest width $\lambda_p$, the power absorption length [5]:

$$
\lambda_p = \frac{2}{\pi} \frac{b(\omega)b_{ext}\omega^2}{(c - (m + a(\omega)) + m_{sup})\omega^2 + (b(\omega) + b_{ext})^2\omega^2}\lambda
$$

(2)

In this particular case, condition (a) is fulfilled if the system’s natural frequency $\omega_n$ for heave equals the frequency $\omega$ of the wave. This can be achieved by adapting the supplementary mass:

$$
\omega_n \equiv \sqrt{\frac{c}{m + a(\omega_n) + m_{sup}}} = \omega
$$

(3)

and applying an external damping $b_{ext}$ equal to the hydrodynamic damping $b$:

$$
b_{ext} = b(\omega_n)
$$

(4)

resulting into following maximum value for the power absorption length:

$$
\lambda_{p,max} = \frac{\lambda}{2\pi}
$$

(5)

In an irregular seaway, these conditions cannot be satisfied for the complete frequency range, so that compromise values for $m_{sup}$ and $b_{ext}$ have to be found, leading to a maximum overall power absorption length.

Concerning criterion (b), slamming occurs when the buoy looses contact with the water surface,

$$
z_{exp} \equiv z - \zeta > d
$$

(6)

The probability of occurrence of slamming in an irregular seaway is given by:

$$
P[z_{exp} > d] = \exp\left(-2 \frac{d^2}{\sigma_{z_{AS}}^2}\right) = \exp\left(-\frac{d^2}{2\sigma_{z}^2}\right)
$$

(7)

$z_{AS} = 2.0$ being the significant amplitude of the relative vertical motion of the buoy, $\sigma_{z}$ denoting the standard deviation of the buoy’s relative vertical position. In order to fulfil criterion (b), the external damping must be increased when operating in spectra characterised by large $H_S$ values compared to the buoy’s draft, so that $z_{AS}$ does not exceed a selected maximum value $z_{AS,max}$.

3.4. Computational tools

For the calculation of the hydrodynamic radiation coefficients and wave exciting forces occurring in linear equation of motions (1), 3D-panel method based software named AQUA+, developed by SIREHNA (Nantes,
France), was used. An example of a mesh representing a wetted buoy surface is shown in Fig. 3.

3.5. Preliminary numerical results

In the first stage of this feasibility study an optimal buoy shape that can provide the best power absorption performance was selected by means of computational evaluation [13]. An optimum appeared to be realised by bi-conical buoy shape with a waterline diameter of 5.0 m, as shown in Fig. 4. For this comparison, optimal values for $m_{sup}$ and $b_{ext}$ were selected; additionally, the external damping was increased in case of severe sea states in order to limit the significant relative motion amplitude to the waterline radius ($z_{rAS,\text{max}} = r$), with exception of cone120, for which the significant relative motion amplitude is restricted to the draft ($z_{rAS,\text{max}} = d$).

4. Experimental study

4.1. Overview

A physical model test program was executed in order to evaluate the numerical results and to verify the linear approach used in the computations. The performance of different buoy configurations was checked under varying conditions. The program consisted of following major parts:

- determination of free-decay curves in still water;
- registration of wave forces acting on the rigidly fixed buoy subjected to regular waves with different period and height;
- evaluation of the power absorption in regular waves with different period and height;
- evaluation of the power absorption in irregular waves.

4.2. Model set-up

Model testing was conducted at Flanders Hydraulics Research in Borgerhout, Antwerp. The experimental facility consists of a wave flume of 70 m length, 4 m width and 1.4 m height, with the test set-up installed at a distance of 15 m from the wave generator, at the central line of the wave tank. The piston type wave generator is controlled by a steering system allowing generation of both regular and irregular wave trains with a maximum height of 0.65 m. The vertical water surface motion was recorded by two wave gauges with 25 Hz sample frequency, situated between the wave flap and the buoy, and behind the buoy, respectively. Tests were also carried out with the wave absorber model being replaced by a wave gauge, so that the actual incident wave train could be registered without being affected by the presence of the model. All tests were conducted at a water depth of 1.0.

The model of the point absorber (Fig. 5) realises the principal concept represented in Fig. 2. The buoy is fixed to a steel rod that translates vertically, guided by two axial bearings attached to a frame. The supplementary mass to increase the absorber inertia is implemented into a closed circuit of a gear belt guided by...
four gears, which is connected to the rod. Wave action induces motion of both the floating buoy and the supplementary mass in opposite senses. The buoy motion is recorded by a multi-rotational potentiometer connected by an axial shaft to one of the guiding wheels.

The damping is realised by a mechanical brake, consisting of a wheel attached to one of the guiding pulleys, and of two curved elements covered with a felt that can be pressed to damp the rotation. A stiff rod connects the mechanical brake to a load sensor, so that the actual damping force experienced by the buoy can be properly determined. The mechanical friction induced by the guiding system, which appeared to contribute considerably to the damping, was determined for varying values of the supplementary mass as well. This was derived from tests in dry equilibrium conditions by recording the acceleration of the buoy and supplementary mass when imposed to the motion by a certain force.

4.3. Buoy shape

Two buoy shapes were investigated. A first test series was carried out with a *bi-cone 60/120* buoy shape, extended with a cylindrical part above the waterline. The diameter of the buoy was 0.31 m, and the linear scale factor of the model when referred to the optimum buoy diameter of 5 m, resulting from the preliminary computational study, was 1:16.

The first test series revealed, however, that non-linear effects due to the variability of the waterline surface with draft and free surface instabilities significantly affect the efficiency of power absorption for that buoy. Therefore, the buoy shape had to be modified in order to realise a compromise between the sensitivity to the vertical wave forces, linearity in restoring force, and the limitation in the hydraulic losses during the motion as observed during the first tests. In respect to the latter, the occurrence of vortex shedding depends on the rounding of the edges of the buoy. As a guide, vortices would be expected to initiate when the local Keulegan–Carpenter number, \( N_{KC} \), exceeds about 3 (see e.g. [14]):

\[
N_{KC} = \frac{\pi \delta}{\alpha}
\]

where \( \alpha \) is the edge radius and \( \delta \) the relative displacement amplitude between the edge and a typical water particle in its vicinity.

The most optimal shape in that respect seems to be a hemisphere coupled with a cylinder. However, the application of such curvature would incur a significant decrease in hydrodynamic damping, as was concluded as a result of the computational study. Therefore, the modified form, a conical shape with top angle 90° is expected to give the optimum solution for the presumptions above. In order to avoid sharp edges, a curvature radius of 0.32r (0.8 m full scale) was introduced as a transition between the conical and cylindrical parts of the buoy. On the other hand, in order to avoid slamming and variability in hydrostatic restoring force, the draft was increased with 1.0 and 2.0 m (full scale), leading to configurations referred to as C90C1 and C90C2, respectively.

In the following, mostly results concerning the configuration C90C1 will be presented.

4.4. Test results and comparison with mathematical model

4.4.1. Decay tests

A first indication about the hydrodynamic behaviour of the tested buoy was obtained by decay tests. They provided verification of linearity of motion and the determination of natural period of the system. In initially still water, the buoy was immersed 0.15 m (model scale) and abruptly released. This test was carried out with varying supplementary mass, so that a relationship between the natural frequency of the system and the supplementary mass was obtained, see Fig. 6. The values of added mass have been derived as well, and are displayed in Fig. 7 together with the theoretically calculated values. The natural period for buoy without the supplementary mass, \( T_{n0} \), has been found to be 0.913, against 0.816 theoretically calculated. For the C90C1 buoy shape, the effect of non-linearity due to variation of hydrostatic restoring force appeared to be negligible if at least half of the conical part remains submerged during the heave motion.

![Fig. 6. Natural period for C90C1 buoy in function of supplementary mass](image)

![Fig. 7. Added mass for C90C1](image)
4.4.2. Exciting force measurement

A second test series was carried out in order to determine the vertical exciting wave force acting on the buoy when stationary held in regular waves with varying period $T$ and height $H$. During these tests, the brake was tightly screwed, so that the wave exciting forces on the buoy were transferred directly by the brake to the force sensor. The presence of second-order phenomena is clearly illustrated in Fig. 8, as the negative extreme values of the exciting force appear to be significantly larger than the positive ones. The amplitudes of the first harmonic component of the exciting force, however, are in good agreement with the values predicted by the numerical method. The visible fluctuation of the force after a number of wave periods is a result of wave reflection from the side-walls of the tank.

4.4.3. Power absorption in regular waves

During power absorption tests in regular waves, the supplementary mass was selected in such a way that the natural frequency was equal to the frequency of the incident wave. For a given wave period and height, several tests were carried out with varying brake force in order to determine the dynamic response as a function of external damping. The total damping force was calculated as the sum of the force registered by the force sensor and the mechanical friction. Next, the resulting captured power was calculated by multiplying the vertical velocity of the buoy and the damping force. Based on the value of the absorbed power, the external damping coefficient could be determined as follows:

$$P = \frac{1}{2} \omega^2 b_{\text{ext}}^2$$

In fact, it is more correct to refer to $b_{\text{ext}}$ as the ‘equivalent external damping coefficient’, since the absolute value of the damping force appeared to be nearly constant during the test, its sign changing with the sense of motion.

The absorber performance is illustrated by Fig. 9 showing a test performed with an optimal value for the external damping, which is reflected in the phase lag of approximately 90° between the buoy displacement and the exciting wave force. Based on Eq. (4), the external damping coefficient should be equal to the hydrodynamic damping coefficient in order to obtain optimal power capture. However, the calculated hydrodynamic damping coefficient for the examined buoy is rather low, so that the resulting motion amplitude is very high exceeding the wave amplitude several times; as an example, in the case displayed in Fig. 9, the heave amplitude of the buoy is nearly three times larger than the wave amplitude. At low damping, however, the related high heave velocity incurs large losses due to viscous effects such as vortex shedding, resulting in undesired energy dissipation. This is reflected in Fig. 10a where both the calculated and measured heave amplitude to wave amplitude ratios are shown as a function of external damping. In case of lower external damping the registered motion amplitude is smaller compared to the calculated values, since the calculations do not account for viscous losses.

This effect has a considerable negative influence on the power absorption length. Fig. 10b also shows significant discrepancies between calculated and measured values for the power absorption length, especially in the low external damping range. On other hand, the agreement between both data improves with increasing damping.

Fig. 10a and b also illustrate the effect of varying the wave period on motion response and power absorption while the natural period of the system is maintained constant. Figs. 11 and 12 reveal a characteristic of the mistuning effect, which can be considered of particular interest for power absorption in natural seaways. It is evident that a discrepancy between the incident wave frequency and the natural frequency of the point absorber

Fig. 8. Modulus of exciting wave force in function of wave period for C90C1  ■ negative; ◇ positive; ● mean; ○ - calculated).

Fig. 9. Power absorption test in regular waves: $T = 1.5 s = T_n$, $m_\text{sup} = 27.5 \text{ kg} = 3.21 \mu V$, $b_{\text{ext}} = 21.43 \text{ kg/s} = 2.84 b(\omega)$ (—: water elevation, -: buoy elevation, - -: exciting force).
leads to a decrease of absorbed power, but this decrease is drastic in the range $\omega < \omega_n$, (long waves), while quite moderate in the range $\omega > \omega_n$ (short waves). This conclusion was already formulated by Ferdinande [15].

In that context, it should be noted that the computed power absorption length drops more rapidly than the measured value. In irregular waves, this can likely result in a better efficiency than predicted.

Finally, Fig. 13 shows the power absorption efficiency of the absorber with two different values of the natural heaving period, the wave height being a parameter. It is noticed that a maximum of at least 140% in power absorption efficiency can be achieved in waves with small amplitude, indicating a clear point absorber performance in which the absorption length is larger than the physical length of the absorber. With increasing wave height, more power may be captured, but at a lower efficiency.

This comparison yields an important issue, namely as the power for both longer and shorter wave periods is obtained at nearly the same efficiency, an increase of the prototype dimensions may result into a higher power absorption at the same extraction rate. It is supposed that a buoy with a waterline radius of 3–4 m (full scale) offers an optimum solution as a point absorber for the considered sea conditions.
location. It was found that the generated spectra contained more energy (about 15%) than intended, see Fig. 14.

In a test series with a particular irregular wave the absorption system was firstly tuned to the peak period and then the damping force was varied. Afterwards the supplementary mass was varied to examine the effect of mistuning on the power absorption efficiency.

It must be noted that the mechanical brake, which proved to simulate successfully the power take-off during tests in regular waves, did not provide a proper solution for external damping when dealing with irregular waves. This is due to the constant absolute value of the damping force irrespective to the buoy motion velocity, implying overdamping in small waves, and insufficient damping for high waves on the other hand. As a consequence, the efficiency of power absorption is decreased, while an enhanced risk exists that the buoy moves out of the water at extreme peaks. In order to improve the irregular wave testing, a power take-off system with constant damping coefficient should be developed Fig. 15.

Under the current conditions, the hydrodynamic power absorption has been obtained as the average of instant power values produced by the time dependent motion speed and damping force over the test duration. As an example, Fig. 16 displays the variation of the power determined in this way.

When testing the C90C1 buoy under $H_s$ class 3 conditions, two values for the supplementary mass were selected, so that the point absorber was tuned to two different frequencies. The power absorption efficiency is displayed as a function of the equivalent external damping coefficient (Fig. 17). A maximum power capture efficiency of 45% was reached. Notably, significantly better results were obtained when the buoy draft was decreased so that...
only the conical part was immersed: with buoy shape cone90, a power absorption efficiency up to 56% can be obtained. Obviously, an increase of power absorption in moderate sea state may be achieved by reducing the absorber draft.

Testing for $H_s$-class 4 was performed with the C90C1 buoy, the supplementary mass being selected in such a way that resonance was obtained with the peak frequency resulting into a power absorption efficiency of 47%, as shown in Fig. 18. However, if the supplementary mass is reduced, an increased efficiency is attained. This is an important issue, showing the advantage of tuning the point absorber to a higher frequency than the modal frequency of the spectrum. Analogous performance of a point absorber in irregular waves was also reported in a study on the AWS [16]. This is a logical consequence of a conclusion of the experiments in regular waves, stating that the condition $u < u_n$ is more detrimental to the power absorption than $u > u_n$. In the current model tests, a reduction of the original supplementary mass by 20% results in an increase of the maximum power absorption efficiency by about 10%. Even if $m_{sup}$ is reduced by one third, almost the same efficiency may be expected as for condition with $u = u_n$. A similar effect has been observed within the tests with $H_s$-class 5, see Fig. 19.

The experimental results are compared with the computational prediction of optimal performance. Although the physical modelling of the external damping was not optimal for irregular waves, it can be stated that for $H_s$-classes 3 and 4 the hydrodynamic power absorption efficiency exceeds the predicted values, compare with Table 2. This can be explained by the fact, that the mistuning effect is less than in the theoretical evaluation; a larger fraction of energy may be extracted over wider range of the frequency domain. For $H_s$-class 5, predicted values are higher than the measured ones, which have to be attributed to the viscous losses, which are more apparent with higher motion amplitudes. However, when the external damping is optimised, significantly higher power absorption is possible which is expected to be about 10%.

The observed buoy motion requires some comment as well. For $H_s$-class 4 the maximum significant motion amplitude reached 0.78 times the draft of the buoy for the lowest value of applied damping. Within the $H_s$-class 5 tests, the significant motion was maximally 96% of the draft, so that the related relative significant motion reached in some cases the dimension of the buoy draft.
On the other hand, if having applied the velocity proportional damping force, this maximum motion amplitude could have been limited. An alternative solution that was considered to prevent slamming in irregular waves consists of increasing the draft, which could enhance the allowable relative vertical motion. However, increasing the buoy draft and the total buoy height consecutively leads to the enhancement of the buoy area facing to the incident waves. The horizontal loading as observed under Hs-class 5 tests is very high, which limits the range of draft regulation. Although horizontal forces have not been a subject of the study yet, they must be accounted for the viability of the system in a severe sea, which is a critical point.

4.5. Estimation of absorbed power

Based on the experimental observations, an estimation can be made for the energy level extraction realised by the full-size absorber. It is assumed that the overall efficiency reaches 58%, resulting in an average power absorption of about 21.6 kW for 5 m diameter buoy. From the current study, however, it has been revealed that the diameter of the absorber can be increased without a loss of efficiency, so that it can be rated higher. A relevant buoy with a diameter of 7 m is estimated to capture an average power of 30 kW. In respect to this data it must be born in mind that they refer to the hydrodynamic performance of the system, and do not take into account friction losses and the efficiency of the electricity generator.

Furthermore, from the constructional and operational point of view, a measure is considered to simplify the performance of the absorber. Instead of varying the supplementary mass so that its value is optimised according to the sea conditions, it is assumed to be constant. For the case, when supplementary mass is best fitted to the considered sea conditions, the expected decrease in overall power absorption efficiency should not exceed 5–7% of that for optimum conditioning. Such a relatively low efficiency decrease is expected because the major Hs-classes (3–5) have small differences in their peak frequencies.

5. Further developments

In a next stage the point absorber should be studied on a larger scale with a simulation of a real power take-off system. The tests with the external damping proportional to the excitation force should reveal more accurate performance data under the irregular wave conditions.

Other research actions are required concerning the location of the wave power plant. So far, all considered spectra are based on observations at one location and one wind sector. Especially the influence of the location may be important due to depth variations, and should therefore be evaluated.

The efficiency of energy conversion is also expected to increase if the amount of available energy is concentrated in a small area. This may be achieved by natural concentration, if locations can be detected near the coast where wave energy converges in a natural way, by comparing wave statistics at different observation sites or, more fundamentally, by means of a mathematical model and a detailed investigation of the local bathymetry. Artificial concentration, i.e. collection of the wave energy from a wide field to a small area, can also be realised by several methods. Lens focussing, for instance, results into high concentrations, but requires the construction of large submerged structures, or converging walls in front of the energy converter. Attention should be paid to the depth dependency of the hydrodynamic behaviour of concentrators, which is of importance in shallow, coastal waters with tidal regime such as the Belgian coastal area. Both model tests on artificial concentration and numerical calculations appear promising.

If several point absorbers are acting at a same location, interaction between them should be investigated as well.

6. Conclusions

In this paper the evaluation of energy production from sea waves is presented with special focus on the application in the Belgian coastal area. The hydrodynamic performance and energy absorption of a point absorber in heave motion of a buoy with controlled supplementary inertia have been examined both on the numerical and physical base.
The effect of the major design parameters on the performance of such absorber in a realistic sea has been discussed.

In the preliminary numerical approach of the study, optimal converter characteristics were determined. The analysis of the device has been performed in the frequency domain and was based on the linear theory of the surface waves, neglecting viscous effects such as vortex shedding, which further proved to have high impact on the prediction of power absorption. The numerical results have been validated by the experimental investigation extended with a 0.31 m in diameter floating buoy.

As a result of this study, the optimal shape and size of heaving buoy has been determined and tested. Instead of a compound submerged shape that consisted of two conical surfaces with top angles 60 and 120°, as revealed from computational study, a 90° cone with cylindrical extension is expected to ensure the optimum hydrodynamic performance. The draft of the buoy was also varied and one can state that an operational adaptation of the draft within 1 m is a potential measure to increase the system absorption efficiency. It is estimated that the absorber is capable to absorb nearly 60% of the energy available in a wave crest width equal to the buoy diameter, averaged over all $H_s$-classes. This fraction depends primarily upon the wave height and reaches 140% for the peak frequency of spectra. Average power capture of 30 kW (or 263 MWh per year), with peaks up to 175 kW (for $H_s$-5) may be obtained per point absorber unit with diameter of 7 m, if both supplementary mass and external damping are controlled operationally.

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