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Effect of Viscous Forces on the Performance of a Surfing Wave Energy Converter

Majid A. Bhinder, Aurélien Babarit, Lionel Gentaz, Pierre Ferrant
LUNAM Université
Ecole Centrale de Nantes
LHEEA – UMR CNRS 6598
Nantes, France.

ABSTRACT
A generic Oscillating Surge Wave Energy Converter (OSWC) has been tested numerically against the impact of the viscous forces. The study makes use of both the linear potential theory as well as the computational fluid dynamics (CFD). A state-of-the-art time domain wave-to-wire numerical model of the wave energy converter (WEC) is developed. Viscous damping is then included using an additional velocity squared term from the Morison equation. A range of possible values for the drag coefficient (following various literary resources) were tested so that to establish the scale of the viscous impact regarding the annual power production (APP) of the WEC. Wave resource considered in these numerical tests cover regular and irregular incident waves. Analysis of the APP demonstrates the importance/sensitivity of having an accurate prediction of the drag coefficient. Moreover CFD has been shown to be a valid tool for evaluation of the unknown drag coefficient. For this the CFD model has been validated by comparing its findings with the previously published experimental (and also numerical) results of a 3D square cylinder. This CFD model is then employed to 3D cases of the surging device in order to refine the estimates of the viscous drag coefficient.

KEY WORDS:
Wave energy converter; WEC; numerical modelling; CFD; viscous damping; drag; Flow3d.

INTRODUCTION
Floating wave energy devices are usually designed to exhibit oscillatory motion in response to the surrounding waves. Interaction of waves and the device oscillations give rise to vortex shedding and the impact of the viscous forces may become important. In terms of the APP (annual power production – measure of the efficiency) of the WECs the role of the resulting viscous drag is to date quite vague. It is of crucial importance that the inter-relation between the viscous drag and the power efficiency of the device is known to the design engineer thus ensuring that the optimized power output is also cost effective. This paper presents a preliminary attempt towards the assessment of the viscous drag in relation to the efficiency of a particular generic WEC designed to oscillate in surge mode only (Fig.1).

When using numerical modelling of WECs in order to determine power production, the BEM (boundary element method) is used, but despite being based on state-of-the-art tools, viscous loss tends to be disregarded. On the other hand CFD models claim to solve the flow field that takes care of the viscous phenomenon. This study benefits from both approaches – the BEM and the CFD – in order to achieve a more robust model for the numerical assessment of a WEC.

(Folley et al, 2005; Hals et al, 2007) has previously included viscous drag into the mathematical models of WECs but the drag coefficients were taken from existing literature.

However in this work we investigate the derivation of these coefficients using CFD and the power output of a floating WEC; with and without viscous drag. The methodology, mathematical model, followed by the setup of the simulations are discussed next.

Fig.1 Schematic of the WEC. Where h= ℓ=10m,and w=7.85m

METHODOLOGY
Case study: a surfing WEC

A 3d surging WEC with dimensions; height: 10m, length: 10m, width: 7.85m as described in (Babarit, 2010) was considered. The device is designed to oscillate in horizontal direction only. The schematic of the
Equation of motion

In time domain, within the frame of linear potential theory, the equation of motion can be written as

\[
(M + \mu_a) \ddot{X}(t) = \left[ F_a(t) - \int_0^\infty K(t - \tau) d\tau \right] - B_{\mu \alpha} \alpha(t) - K_{\alpha \alpha} X(t) + F_{\text{viscous}}(t)
\]

(1)

Here:

- \( X(t) \): the displacement of the body
- \( \dot{X}(t) \): velocity
- \( \ddot{X}(t) \): acceleration

- \( F_a(t) \) is the excitation force of the incident waves. In irregular waves, for a given sea spectrum \( S(f) \), a typical representation of the excitation force, is represented as

\[
F_a(t) = \sum A_i F_{\alpha i}(f) e^{-i(2\pi f t + \phi_i)}
\]

in which the amplitudes \( A_i \) are as given and \( A_i = \sqrt{2S(f_i)} \Delta f \); the phases \( \phi_i \) are set randomly and \( F_{\alpha i}(f) \) are the complex excitation force coefficients which were calculated in the frequency domain.

- \(-\mu_a \ddot{X}(t) - \int_0^\infty K(t - \tau) \dot{X}(\tau) d\tau\) is the radiation force.
- \( \mu_a \) is the added mass coefficient and \( K \) is the retardation coefficient. These time domain coefficients were obtained from frequency domain coefficients using Ogilvie’s formula.

- \( B_{\mu \alpha} \) and \( K_{\alpha \alpha} \) are the Power Take Off (PTO) damping and stiffness coefficients respectively.
- \( M \) is the mass of the body

- \( F_{\text{viscous}}(t) \) is an additional force which exists only when viscous damping has been taken into account. Details of modelling this viscous force are presented in the following section.

Modelling of the viscous force

In the equation of motion, viscous effects are modeled as an additional quadratic damping source. It is written:

\[
F_{\text{viscous}} = -\frac{1}{2} C_{d} \rho \left[ (V - X_a)(V - \dot{X}_a) \right]
\]

(2)

With:

- \( A \) being the area perpendicular to the motion, in our case it is \( A_f \)
- \( C_{d} \) the drag coefficient
- \( X_a \) the velocity of the incident wave field.

Estimation of the viscous damping coefficient

The drag coefficient depends on the geometry and on the conditions of the flow. Therefore a non-dimensional Keulegan Carpenter number (KC) becomes relevant. The KC number is defined as;

\[
KC = \frac{U_a}{T} \frac{T}{D}
\]

(3)

Where \( U_a \) is amplitude of the velocity of moving structure, \( T \) the time period and \( D \) the relevant dimension of the rigid structure. For an oscillating flow, KC number can be written as (Sumr and Fredsoe, 2006).

\[
KC = 2m / D
\]

(4)

When considering the above mentioned viscous force (Eq. 2) the drag coefficient is a prerequisite which can be chosen from literary resources or, alternatively, one could adopt the experimental procedure. However CFD does provide an alternative to the complex and time consuming experimental setup. In this work Flow3d – a commercial CFD package – has been used for the viscous force calculations and the CFD lead values of the force coefficient have been consulted along with the published experimental and numerical work. A validation study of the CFD model for an oscillatory heaving cylinder has already been presented (Bhinder et al, 2011).

The CFD solver is based on RANSE (Reynolds Averaged Navier Stokes Equations) and therefore the viscous force is automatically being treated in the equation of motion. Flow3d has previously been used for wave propagation applications including floating wave energy converter (Bhinder et al, 2009). Further details on the solver and the meshing methodology can be traced in (Flow3d Manual, 2011).

Calculation of the APP

Once one has been able to estimate the \( C_d \), the equation of motion (Eq. 1) can be solved. In this study, it was done using the MATLAB solver ode45. Subsequently, the instantaneous power \( (P_{\text{inst}}(t)) \) is given by

\[
P_{\text{inst}}(t) = B_{\mu \alpha} \ddot{X}(t) + K_{\alpha \alpha} X(t)
\]

(5)

Over the duration of the simulation, the mean power \( \left< \frac{P}{T}(H_s, T_p) \right> \) is as follows:

\[
\left< \frac{P}{T}(H_s, T_p) \right> = \frac{1}{T} \int_0^T p_{\text{inst}}(t) dt
\]

(6)

Then, the Annual Power Production (APP) of the device is examined in accordance with the Yeu island site where the irregular sea states are described by the Bretschneider spectrum defined as

\[
S(f) = \frac{A}{f^B} e^{-f^A}
\]

(7)

Here \( H_s \) and \( T_p \) refer to significant wave height and peak wave period respectively. The sea state statistics \( S(H_s, T_p) \) of the Yeu island site located on the west coast of France are shown by the scatter diagram of (Fig. 2). Using these statistics and Eq. 7, finally the annual power production (APP) of the device is calculated by;

\[
\frac{A}{f^B} e^{-f^A}
\]

\[
A = \frac{5}{16} H_s^2, \quad B = \frac{5}{4} \left( \frac{1}{T_p} \right)^{\frac{3}{4}}
\]

(8)

Here: \( H_s \) and \( T_p \) refer to significant wave height and peak wave period respectively. The sea state statistics \( S(H_s, T_p) \) of the Yeu island site located on the west coast of France are shown by the scatter diagram of (Fig. 2). Using these statistics and Eq. 7, finally the annual power production (APP) of the device is calculated by;
\[ APP = \sum_{H_r, T_r} P_r(H_r, T_r) C(H_r, T_r) \]  

(9)

**Fig. 2 Contour plot of sea state at the Yeu site**

**RESULTS**

**Estimation of the viscous damping coefficient using CFD**

Case studies considered for the CFD simulations are shown in Table 1.

<table>
<thead>
<tr>
<th>Case-Study</th>
<th>Amplitude</th>
<th>Period</th>
<th>KC</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1</td>
<td>1 m</td>
<td>6 s</td>
<td>0.6</td>
</tr>
<tr>
<td>B2</td>
<td>2 m</td>
<td>7.7 s</td>
<td>1.6</td>
</tr>
<tr>
<td>B3</td>
<td>3 m</td>
<td>10 s</td>
<td>3.0</td>
</tr>
</tbody>
</table>

For a typical simulation the dimensions of the computational domain were X (horizontal) = 120m, Y = 30m, and Z (vertical) = 40m with number of cells being 1073600 where the smallest cell size was 0.4m. However, stretched cells were placed adjacent to the boundaries of the domain so that to minimize the reflection effect (see Fig. 3). Moreover due to symmetrical representation only half of the device was modelled along the y-direction (i.e. length of the device, see: Fig. 1). Specifications of the computational resource used in this study are as follows:

- Ram: 6GB, processor: Intel(R) Xeon(R) CPU E5620 @2.40GHZ
- System: Windows 7 Professional 64 bits.

For a 60s simulation the CPU time was recorded to be 58.16 min.

Mesh independence of the results reported was insured by convergence check (see: Table 2). Following results of mesh convergence test Mesh1 (of Table. 2) was chosen for all simulations.

<table>
<thead>
<tr>
<th>Mesh</th>
<th>Total cells</th>
<th>Smallest cell</th>
<th>( Cd )</th>
<th>( Cm )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1073600</td>
<td>0.4</td>
<td>1.85</td>
<td>1.81</td>
</tr>
<tr>
<td>2</td>
<td>2857372</td>
<td>0.3</td>
<td>1.85</td>
<td>1.83</td>
</tr>
<tr>
<td>3</td>
<td>6026000</td>
<td>0.2</td>
<td>1.87</td>
<td>1.83</td>
</tr>
</tbody>
</table>

Fig. 4 to 6 show the fluid force applied on the body calculated with Flow3D and the best fit of this force obtained using the Morison equation. The agreement of the two forces appear to be of rather good quality in the first two cases (Fig. 4 and 5) and reasonably acceptable in the last case (Fig. 6).

For each case-study the evaluated drag coefficients and added mass coefficients are shown in Table 3. One can see that the order of magnitude of the drag coefficient is found to be about 2. It is also observed that \( Cd \) decreases with an increasing KC number whereas the added mass coefficient is almost constant, i.e. 1.8.

<table>
<thead>
<tr>
<th>KC</th>
<th>( Cd )</th>
<th>( Cm )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.6</td>
<td>2.42</td>
<td>1.78</td>
</tr>
<tr>
<td>1.6</td>
<td>1.93</td>
<td>1.80</td>
</tr>
</tbody>
</table>

**Fig. 3 Computational domain of the CFD simulations**

**Fig. 4 Force comparison for case study B1**

**Fig. 5 Force comparison for case study B2**
Contour profiles of dissipation of the turbulent energy in the vicinity of the oscillating device reveals the generation of a vortex formation around each sharp corners. The turbulent energy dissipation of the first 2-cycles of oscillation for case B3 is shown in Fig. 7.

Since the dimensions of the WEC resemble a square cylinder therefore these CFD results can be consulted by juxtaposition of our results with the one’s present in Table 4 which has been taken from the work of (Zheng and Dalton, 1999) where drag and inertia forces for a square cylinder have been presented along with references from experimental work. Although the order of magnitude is similar, one can see that in our case the observed drag force is lower than results obtained by these authors.

<table>
<thead>
<tr>
<th>KC</th>
<th>Zheng &amp; Dalton calculated $Cd$</th>
<th>Scolan &amp; Faltinson calculated $Cd$</th>
<th>Bearman et al. experimental $Cd$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3.01</td>
<td>4.39</td>
<td>3.19</td>
</tr>
<tr>
<td>2</td>
<td>3.21</td>
<td>3.61</td>
<td>3.15</td>
</tr>
<tr>
<td>3</td>
<td>3.19</td>
<td>3.19</td>
<td>2.84</td>
</tr>
</tbody>
</table>

Fact that the width of the WEC is smaller than the other two equal dimensions, this differentiates our case-study from that of a square cylinder hence a higher value of the $Cd$ was expected. The reason why the magnitude of this drag coefficient is lower than the case of a square cylinder is under investigation.

Effect of viscous force on the APP of the WEC

Overall picture of performance of the WEC is shown via numerically computed power matrix (Fig. 8) which gives the average value of power production for each corresponding set of $Hs$ and $Tp$. It is reasonably prominent that when viscous damping is taken into account the predicted performance is reduced to almost 60 %. Also the corresponding absorbed power as a function of wave frequency is shown in Fig.9 where the lower peak of the absorbed power refers to viscous force scenario.

![Fig. 8 Contour plots of the power matrix; (a) without drag term, Cd=0, (b) with drag term,Cd=1.8](image-url)
Finally comparison of the power production with and without viscous term has been shown in Table 5.

<table>
<thead>
<tr>
<th>Power Output</th>
<th>Without viscous drag</th>
<th>With viscous drag (Cd=1.8)</th>
</tr>
</thead>
<tbody>
<tr>
<td>APP</td>
<td>114 KW</td>
<td>74.4 KW</td>
</tr>
</tbody>
</table>

It is shown that the viscous drag (Cd = 1.8) causes quite significant loss (i.e. 34.7%) in the APP of this specific device. In real sea scenario the instantaneous values of exact KC number cannot be determined however for a specific device at precise location a range of possible KC values can be evaluated following sea statistics and device dimensions. Then power loss against possible values of the expected drag range would provide a better insight into the design of the WECs. For this, Cd was successively increased and the corresponding APP has been plotted as shown in Fig.10.

Following the methodology presented here the drag coefficient of any complex shaped structure can be deduced using CFD and then the time-domain model offers a robust approach for numerical modelling of the WECs. Otherwise a comprehensive simulation of irregular wave propagations using CFD is somewhat challenging and time consuming.

In this study the WEC responds only in one degree of freedom and in this case PTO is also providing considerable damping but even so the power loss due to the viscous phenomenon is significant. Thus for one degree of motion WEC especially for flap type devices it has been demonstrated that the viscous drag plays an important role and hence requires further examination. However for pitching devices the role of viscous drag might be different and would be dealt with in future studies.

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