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Underwater Geometry Optimization for an Oscillating Water Column Ocean Wave Energy Converter

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Abstract

This paper describes an experimental programme designed for the comparison of the performance of oscillating water column (OWC) underwater geometry. The process described utilises two-dimensional (2D) Particle Imaging Velocimetry (PIV) data in conjunction with wave probe and pressure transducer data to provide qualitative and quantitative information. At present the testing scheme is limited to monochromatic waves and 2D based assumptions. A method is presented for qualitative comparison of candidate geometry. It is concluded that average-kinetic energy fields are a suitable qualitative process for ranking of candidate geometry.

Nomenclature

dx, dz	Pixel width and pixel height (mm)
$E_{k(i,j)}$	Kinetic energy of pixel equivalent water particle (J/m)
$\overline{E}_{k(i,j)}$	Mean kinetic energy of pixel equivalent water particle for overlapping fields (J/m)
f	Wave frequency (Hz)
H_u	Wave height, zero up-crossing, vertical distance between a trough and successive crest (m)
N	Number of overlapping fields
$v_{x(i,j)}, v_{z(i,j)}$	Horizontal and vertical velocity components (m/s)

Introduction

Ocean wave energy remains a nascent technology, however there are indications it is gaining a reputation as a viable contender in the renewable energy future, evidenced by the recent award of several grants to wave energy projects by the Australian Renewable Energy Agency (ARENA), formerly the Australian Centre for Renewable Energy (ACRE) [1].

The oscillating water column (OWC) is a type of wave energy converter whose operation is analogous to a blow hole; wave action drives free surface motion and a corresponding air volume flux above the free surface through a bi-directional turbine for energy extraction. Typically, data obtained in model experiments on OWCs are outputs from wave probes and pressure transducers. This data enables determination of the incoming energy flux and the energy flux at the simulated power take-off which can be used to estimate the power available for extraction at full scale.

The process of how the energy transformation takes place is of interest for purposes of next generation design of the underwater geometry of the OWC. Two-dimensional (2D) particle imaging velocimetry (PIV) was conducted at the centreline plane of a three-dimensional generic forward-facing bent-duct OWC in the Australian Maritime College Towing Tank for monochromatic seas. The 2D velocity fields were phase-averaged over a wave cycle (see figure 1). Visualisation of the velocity fields as quiver plots showed the average bulk flow in and around the device including: water column slosh, vortices and an outflow jet. The velocity fields are additional tool for future design of OWC geometry and CFD validation.

This paper describes the approach that will be used to perform work under the ARC linkage grant LP110200129; the primary objective of which is to improve the underwater geometry of the forward-facing bent-duct OWC in terms of manufacturability and energy conversion efficiency.

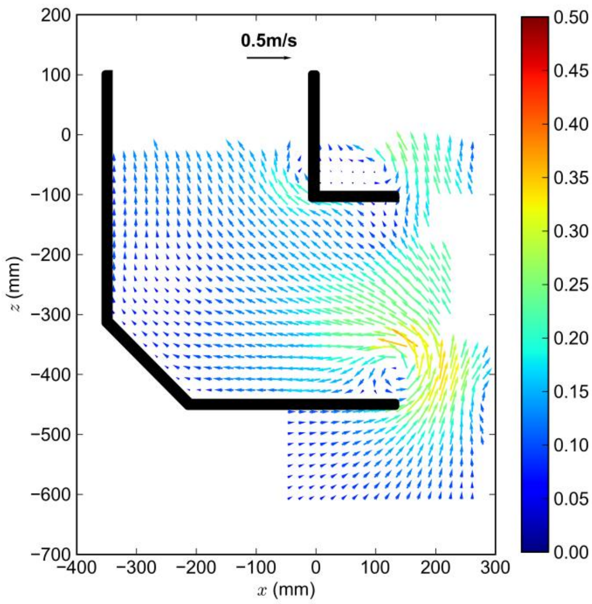

Figure 1. Example velocity field of 2D PIV data captured for a forward-facing bent-duct OWC. For clarity only ¼ of vectors available are shown. Velocity field consists of a mosaic of seven separate fields of view which were phase-averaged via curve fitting for the monochromatic wave condition of h=0.07m, f=0.050Hz. Upper and lower lips of OWC geometry are superimposed as thick black lines.

Methodology

The methods described in this paper follow on directly from work recently completed at the Australian Maritime College (AMC) [2–4].

Experimental Setup

As for previous similar experiments [2], all experiments are conducted in the AMCs 100m long 3.5m wide, 1.5m deep towing tank. The test program involves several phases:

- Commissioning of new PIV equipment;
- Test for repeatability by comparing results with existing data for existing geometry;
- Investigating 3rd velocity component/differing planes;
- Differing geometry (the main objective).

The experimental setup for the standard test case is shown in figure 2. All equipment is mounted to the towing tank carriage (not shown). During this experimental test series the carriage is kept stationary.

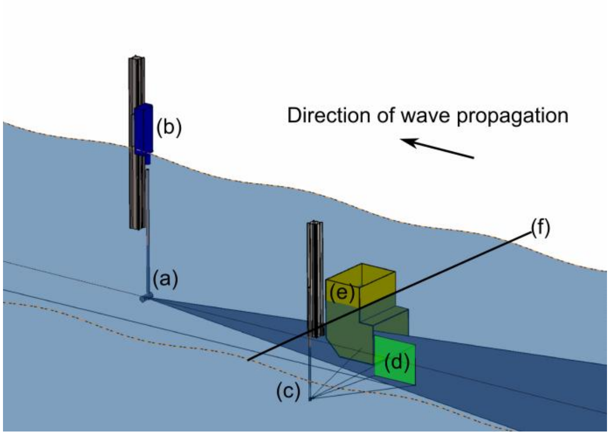

Figure 2. Experimental setup in the towing tank. (a) Laser sheet optics (b) Laser (c) Camera borescope (camera not shown) (d) field of view (e) OWC model (f) Datum at still water level

Data Types

Newly acquired PIV equipment enhances the capability of the Towing Tank to enable 2D PIV acquisition whilst the carriage is underway. The arrangement of PIV equipment is shown in figure 2 and consists of: a) double pulsed Nd Yag laser (120 mJ, 10Hz); b) underwater laser-sheet optics (divergence angle ~ 10.2 deg in freshwater); c) borescope (giving optical access to sCMOS camera: 16bit, 2560×2160pixels, underwater divergence angle of 20.2deg×17.1deg, via an 85mm lens fitted with a high pass filter).

Each OWC model has an array of resistance type wave probes, consisting of up to 17 probes arranged both inside the OWC chamber and at the front face. The wave probe data has multiple purposes: it is used to identify the free-surface so that masking can be applied to PIV image pairs which intersect the free-surface, and can be used for energy and power based calculations (see Fleming *et al*.[3]).

An additional resistance wave probe, mounted adjacent to the datum of the OWC model, provides a signal for phase-averaging (described later). The datum of this probe is the intersection of the front face of the model and the still water level (item (f) in figure 2). This wave probe is identified as the "phase wave probe".

Two pressure transducers monitor OWC air chamber pressure and are used in power take-off calculations. The power take-off is simulated by a 58mm orifice plate.

Particle Seeding

Self-manufactured neutrally-buoyant fluorescent seeding particles with a size range of 32 – 80micron are premixed in a tank (~100litre capacity) by circulating the water in the tank with a suitable pump. The concentrated solution is then introduced into the test volume and the seeding density is verified via the PIV system.

Model Geometry

Three variations of the generic geometry will be tested in the first iteration of experimentation. The profiles of the new geometry are commercially sensitive so will not be disclosed. The form of the geometry was derived using a semi-parametric method. Similarity between geometry forms is maintained using the following constraints:

- The model width is 500mm;
- The depth of the lower lip is 440mm;
- A constant chamber length to underwater cross-sectional-area ratio is maintained;
- A constant 58mm diameter orifice is used to simulate power take-off.

Experimental Data Acquisition

The main purpose of the experimental test programme is to acquire sufficient data to identify the most promising next generation underwater geometry from the available candidates. Due to the desire to reduce experimental testing time and relatively low PIV data acquisition rates (10Hz), the initial testing matrix (Table 1) consists of a single monochromatic wave condition. The rationale for this is described in the *results* section. Multiple fields of view required to cover the spatial area of interest, while repeats are used for uncertainty reduction purposes.

Variable	Number	Values
Wave height (H_u)	1	0.07m
Wave frequency (f)	1	0.50Hz
Model geometry	3	Three variations of geometry
Field of view	5	Positioned to cover area of interest – inside and outside OWC
Repeats	2	At least two repeats to provide at least 800 PIV image pairs for all of the combinations above

Table 1. Initial PIV test matrix for the geometry optimization test program.

An extended test programme will be conducted on the highest ranking geometry as identified in the initial test series. The extended testing programme is shown in Table 2, the purpose being to acquire further data to enable a more detailed comparison of performance with the starting (generic) geometry.

Variable	Number	Values
Wave height (H_u)	1	0.07m
Wave frequency (f)	1	0.44, 0.57, 0.77Hz
Model geometry	1	The best candidate geometry identified from initial testing
Field of view	5	Positioned to cover area of interest – inside and outside OWC (up to 5 positions)
Repeats	2	At least two repeats to provide at least 800 PIV image pairs for all of the combinations above

Table 2 Extended PIV test matrix for geometry with highest performance rating

Data Reduction

PIV data reduction is performed differently for the initial and extended scenarios. The purpose of the initial tests is to quickly rank the performance of the candidate geometry. Results presented in this paper argue that a suitable means to rank is to qualitatively rank geometry based on normalised averaged kinetic-energy of the velocity fields. Using the 2D assumption (as in [3]) that there is zero out of plane flow; 2D kinetic energy of the water particles is given by

$$E_{k_{(i,j)}} = \frac{1}{2}\rho_w \left(v_{x_{(i,j)}}^2 + v_{z_{(i,j)}}^2\right) dx\, dz \qquad (1)$$

where (i,j) represent a pixel, ρ_w is water density, dx, dz are pixel width and pixel height respectively, $v_{x_{(i,j)}}, v_{z_{(i,j)}}$ are velocity components.

The average-kinetic energy field for a set of spatially related velocity fields is given by

$$\overline{E}_{k_{(i,j)}} = \frac{1}{N}\sum_{n=1}^{N} E_{k_{n(i,j)}} \quad (2)$$

where N is the number of kinetic energy fields. Average based results presented in this paper have the additional constraint of $N > 40$ meaning that areas of insufficient/invalid data are not included, namely areas in transient free surface locations.

Different fields of view of like fields (velocity fields or derived) are assembled in a mosaic by the following process:

1. A common vector grid is derived based on the fields of view to be merged;
2. Each component of the source field is interpolated to the new vector grid using cubic spline interpolation with pre-filtering (achieved using the SciPy function ndimage.map_coordinates [5]);

Gaussian weighted averaging is applied to the overlapping pixels to merge the overlapping data. The premise for using Gaussian weighting is based on the reduction in confidence of PIV data towards the edges of the PIV velocity fields.

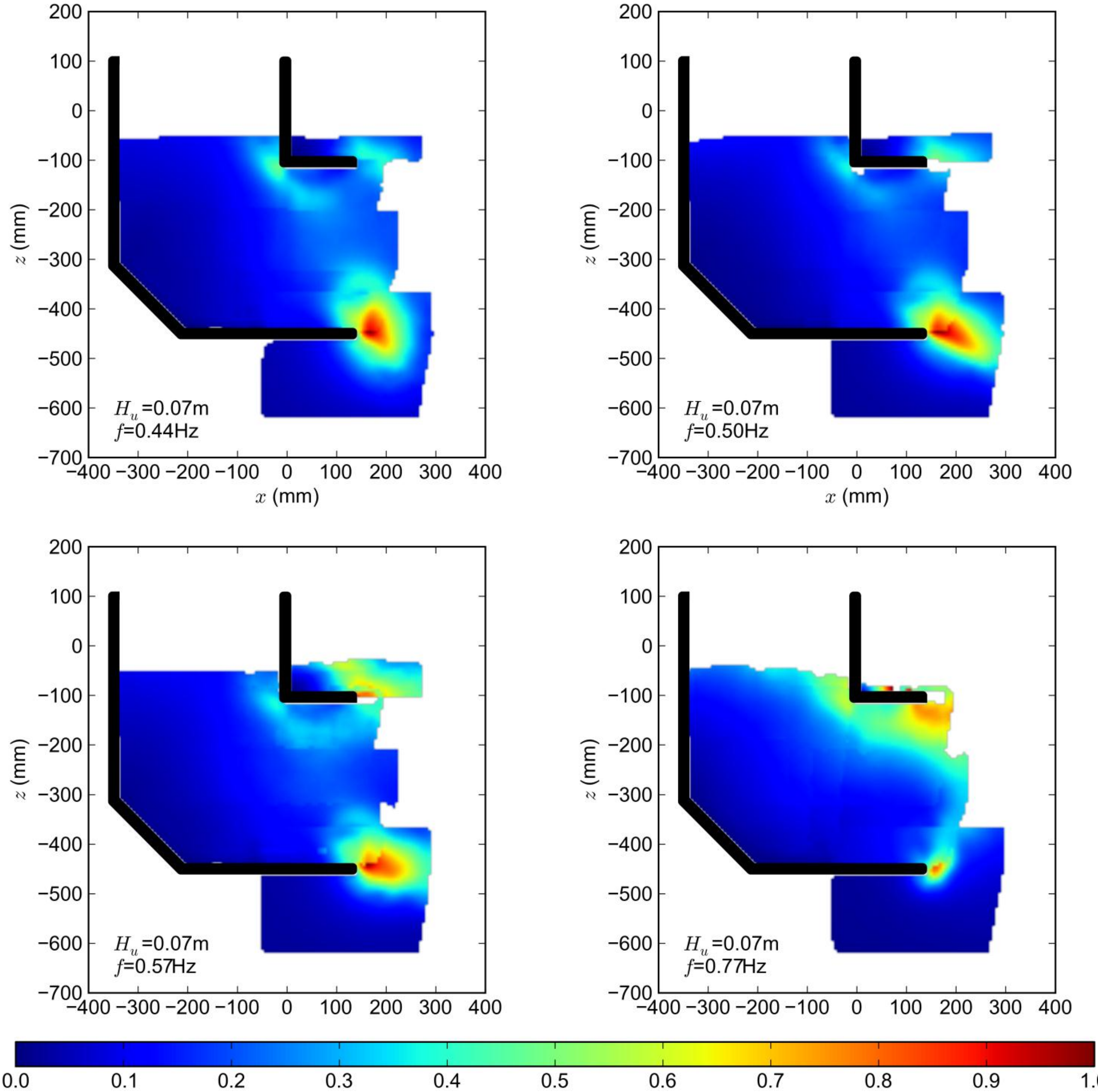

Figure 3. A mosaic of the normalized average kinetic energy of the instantaneous velocity fields for existing experimental data for the generic forward-facing bent-duct oscillating water column corresponding to the monochromatic wave conditions as overlaid. The upper-lip and lower-lip of the geometry are overlaid as thick black lines.

Detailed Comparison

Presenting the methodology for the detailed comparison of differing geometries is beyond the scope of this paper. However, the comparison will use the following assumptions:

- Models and flow are two-dimensional;
- Models are the same scale;
- Models are similar in operational range.

Data analysis utilise curve-fitting phase-averaging and Energy Balance methods (previously been presented by Fleming *et al.* [3,4]). The energy balance method permits direct comparison between the differing geometry of the following:

- Power at the power take-off (phase-based over a wave cycle);
- Kinetic energy of vortices (phase-based).

Results and Discussion

Results presented here demonstrate the methodology used to qualitatively compare the performance of existing and new OWC underwater geometry as part of the initial phase of testing. Figure 3 shows the simple averaging technique applied to existing data for the *generic* forward-facing bent-duct OWC model. The experimental setup and process of data acquisition are described by Fleming *et al* [2]. Each field represents the normalised average-kinetic energy for a single wave condition, figure 4 shows the average-kinetic energy for all of the wave conditions tested.

With exception of the highest frequency wave (f=0.77Hz, lower left), the fields exhibit similar characteristics:

- A hotspot sits adjacent to the lower lip which is associated with vortices generated off the lower lip;
- A hotspot (lower intensity) sits adjacent to the apex of the upper lip and chamber front wall, associated with separation of flow as it passes the sharp corner;
- A gradient of reduced energy intensity from front to rear (right to left) implies unequal energy distribution.

Based on these observations we postulate that hot spots and gradients highlight inefficiencies associated with the conversion process of the underwater geometry. It then follows that this process is also valid for analysis of the performance of the underwater geometry in irregular seas.

The comparison process will initially be qualitative in that ranking of geometry performance will be achieved by visual comparison of the average-kinetic energy fields. In future a quantitative process may be desirable however careful consideration of the measurement window is apparent since there is considerable flow activity outside geometry boundary (this is also necessary for the detailed analysis which requires a suitably defined measurement window).

Assuming a suitable measurement window can be defined, a quantitative comparison could consider the standard deviation of the energy by a piecewise process yielding a single value. Geometry with a lower standard deviation of the average-kinetic energy field would then be considered more efficient in terms of energy conversion.

Conclusions

This paper has described an experimental test programme with the primary aim of developing experimental techniques for energy conversion performance comparison of OWC underwater geometry. Initial performance comparison is a qualitative process relying on average-kinetic fields produced from 2D PIV velocity fields. Example average-kinetic energy fields produced from existing data show areas of inefficiency as 'hotspots' and it is postulated that minimizing hotspots and gradients will minimize energy losses; yielding more efficient underwater geometry.

The experimental and post-processing techniques described here will be applied during planned future investigations involving more complex wave sequences, such as polychromatic waves and irregular wave spectra.

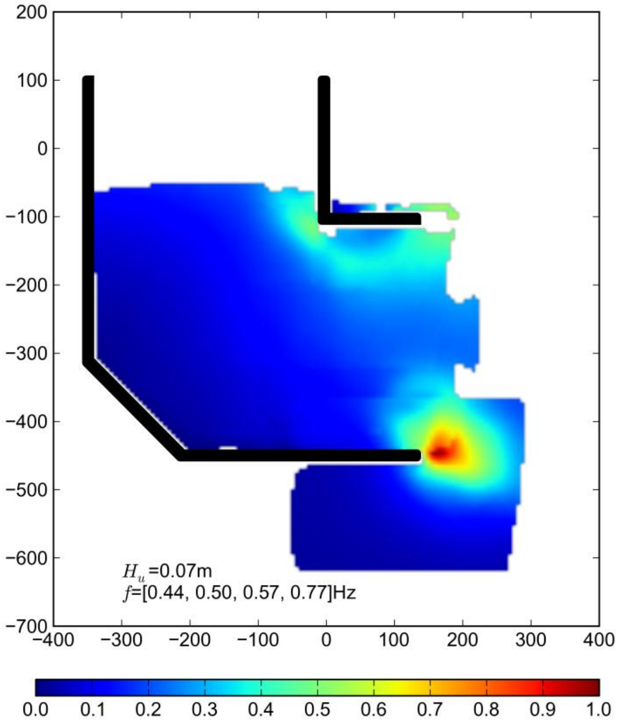

Figure 4. Average of all four energy fields from figure 3.

Acknowledgments

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