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A PIV investigation of OWC operation in regular, polychromatic and irregular waves

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A B S T R A C T

Model scale testing plays an essential role in the development and evaluation of wave energy converters and is generally performed in either regular or irregular waves. A less frequently used intermediate wave type is a polychromatic wave which has properties of both. This paper presents methodology for data processing and results from experiments in all three wave types using PIV to capture the velocity fields in and around an oscillating water column. Two methods for the merging of data in the time domain from multiple runs are presented for data sources with high and low sampling rates.

The operation of the OWC in regular, polychromatic and irregular waves was compared using a novel application of normalised histograms and revealed numerous differences including the frequency and size of vortices. A linear relationship was identified between total kinetic energy and energy contained within vortices in the irregular wave. Polychromatic waves successfully represented the power output of the device in irregular waves but more investigation is required into whether they can represent the impact of vortices on device operation. The techniques developed enable evaluation of WEC design changes using PIV in the time domain, and therefore in a more realistic sea state.

1. Introduction

Capturing wave energy and the efficient conversion of it to a useful energy source can provide a significant opportunity to diversify our energy supply and reduce reliance on fossil fuels. There are a number of wave energy converter (WEC) designs which have shown this ability, one of which is the oscillating water column (OWC) [1]. To further the development of OWC design and progress towards economic viability further research needs to be undertaken to gather a detailed understanding of the device's operation and to identify opportunities to maximise its efficiency.

The testing of full scale prototypes is both expensive due to construction and installation costs and time consuming, as devices need to be on location for an extended period to gather data in a wide range of conditions. Model scale testing provides an alternative that is significantly cheaper and also allows testing in highly controlled conditions, which provide high quality and repeatable data. The use of scaled models also allows numerous data gathering techniques such as flow visualisation that are impractical to apply at full scale.

Particle image velocimetry (PIV) is an experimental technique which allows the calculation of velocity fields without any interference with the flow itself. PIV is performed by initially seeding the fluid with neutrally buoyant particles, which are subsequently illuminated using a light sheet generated using a high powered laser. Particles follow the movement of the water and a camera is used to capture two images at a small time interval. Images are then subdivided into interrogation windows and the fluid velocity at each of these windows is calculated using cross-correlation [2]. PIV has been used to analyse a wide range of flow fields involving waves including investigations into ship wake in regular waves [3] and investigations into breaking waves [4].

Model scale testing is generally performed in a wave basin or flume where waves are artificially generated. These waves generally fall into one of two major categories; regular [5,6] and irregular [7,8]. Regular waves consist of a sinusoidal wave with a single height and frequency and are used to gather data on the device at one very specific condition. Irregular waves consist of a wave spectrum containing a range of heights and frequencies and provide conditions much closer to those a device may experience in real-world conditions. A number of different spectrums have been

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developed based on hind cast wave data to represent various ocean wave conditions. The JONSWAP spectrum represents wave conditions with a reduced fetch and is commonly used to test wave energy devices [9]. As an irregular wave does not repeat like regular waves, techniques such as phase averaging cannot be applied to analyse data.

In a recent study it was shown that an intermediate wave type, a polychromatic wave, can offer some properties of both regular and irregular waves [10]. This wave type features multiple frequency components similar to an irregular wave, yet by restricting the wave to a finite number of components, the wave can have a relatively short repeating interval similar to regular wave. Having a repeating interval of manageable size allows the devices performance to be analysed using well established methods developed for regular waves such as phase averaging. Importantly this wave offers a wave profile with a variety of peak and trough heights which reduces the impact of unrealistic harmonic effects on an OWC's operation. These harmonic effects are non-linear and can result in inaccurate findings if linear superposition is utilised [10].

PIV has previously been successfully used to analyse the operation of OWC's in regular waves [11–14]. These studies adopted phase averaging to analyse velocity fields within and around OWCs. As a method for the analysis of OWC velocity fields Fleming et al. developed an energy balance [15]. This study used PIV velocity fields to identify and quantify energy sources, stores and sinks that are present during OWC operation. Energy stores within the device included water column heave and slosh, chamber air pressure differential and the generation of vortices. A key finding of the study highlighted that energy contained within vortices was not available to the power take-off (PTO), and therefore was a significant inefficiency in the operation of the device. Thus far this analysis has only been applied to an OWC in regular and polychromatic waves [10].

This paper presents and demonstrates a procedure and data processing methodology to obtain the velocity fields of an OWC in irregular waves. The paper explores the difference in OWC operation in regular, polychromatic and irregular waves through the use of components of energy balance is explored, in particular looking at the presence of vortices which occur during the operation of the device. Data is presented using histograms to show the distribution of key results relating to the operation of the OWC. To the author's knowledge, this is the first study to apply PIV to the study of any type of WEC in irregular waves.

2. Methodology

2.1. Experimental setup

Experiments were performed in the Australian Maritime College's Towing Tank. This facility has a length of 100 m, width of 3.5 m and depth of 1.5 m and a single hydraulically powered paddle-type wave maker [16]. A sloped beach at the end of the tank reduced reflections.

A 1:30 scale model of a generic forward facing bent duct OWC with constant cross section (shown in Fig. 1) was positioned centrally within the tank and secured rigidly to the carriage above with the chamber opening directly facing the wave maker in the head seas condition. The model was constructed of 6 mm clear acrylic and had an internal width of 506 mm. The draught of the device allowed a distance of 1060 mm between the lower lip and the bottom of the tank. An orifice with diameter of 50.8 mm simulated the PTO and was located centrally in the roof of the chamber. The orifice size was selected to give the device the desired damped natural frequency of approximately 0.55 Hz (10 s period at full scale). The damped natural frequency was determined

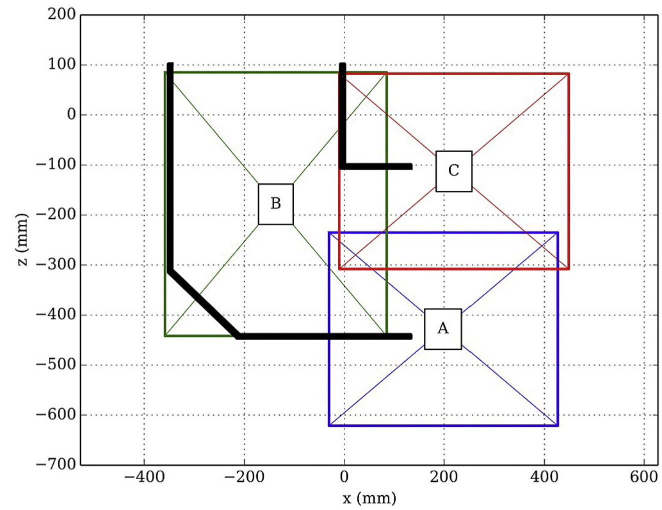

Fig. 1. Cross section of the forward facing bent duct OWC (thick, black) used in the experiments and the three fields of view captured using the PIV equipment (A, B, C). The free surface is at z = 0 mm.

experimentally by determining the frequency at which the greatest chamber elevation, relative to wave height, occurred within the chamber using regular waves of a single height. This damping method was selected due to both its simplicity and ability to represent the non-linear pressure-flow relationship of an impulse turbine [17].

Water elevation was measured using an array of nine twin-wire capacitance type wave probes placed both within and in front of the device in the same configuration shown in Ref. [10]. A 2D polynomial was used to interpolate between the measured free surface elevation at each array location. The incoming wave elevation was measured using an additional wave probe, the incident wave probe, located adjacent to the front of the chamber and offset approximately 300 mm from the side of the tank and 450 mm from the centreline of the OWC. This distance was considered sufficient to minimise the impact of the OWC on the measured incident waves.

The air pressure differential within the chamber was measured using two Endevco Model 8510B-2 pressure transducers, with the signal conditioned using an Endevco 136 Voltage amplifier. These were placed at the top of the chamber approximately halfway between the orifice and the sidewalls on either side of the device. Data from the wave probes and pressure transducers was captured using a National Instruments PCI-6254-M DAQ card at a rate of 500 Hz. After capturing, wave probe and pressure transducer data was processed with a digital low pass 5th order Butterworth filter with a cutoff frequency of 12.50 Hz in both directions to remove the minimal noise in the signal while maintaining the signals phase [18].

Mitchell Ferguson et al. [14] used 2D PIV to capture velocity fields within the same OWC geometry and have shown that the majority of the flow occurs in the longitudinal plane. A similar approach was adopted for the present study where underwater optics were used in conjunction with a 120 mJ Nd-Yag laser to project a light sheet in a longitudinal plane along the centreline of the model (Fig. 2). The water in the vicinity of the device was seeded with neutrally buoyant fluorescing particles of between 36 and 75 μm diameter. A single sCMOS camera (2560 × 2150 pixels) captured image pairs at a rate of 15 Hz with an inter-frame time of 10 ms from outside of the tank and perpendicular to the light sheet. Three fields of view were required to capture the full field of