



**UTS**

**UNIVERSITY  
OF TECHNOLOGY  
SYDNEY**

Faculty of Engineering & Information Technology

**EXPERIMENTAL AND NUMERICAL  
STUDY OF A FIXED MULTI-  
CHAMBER OSCILLATING WATER  
COLUMN DEVICE (MC-OWC)**

A thesis submitted for degree of

**Doctor of Philosophy**

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## EXPERIMENTAL AND NUMERICAL STUDY OF A FIXED MULTI-CHAMBER OSCILLATING WATER COLUMN DEVICE (MC-OWC)

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## Certificate

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## **Abstract**

This thesis focuses on preliminary investigating the hydrodynamic performance of a fixed Multi-Chamber OWC (MC-OWC) wave energy converter, which consists of a linear array of four OWC chambers aligned in the same direction of the incident wave propagation. These investigations address the gaps found in previous works by putting forward detailed explanations of the effect of wave height, wave period, device draught and power take-off (PTO) damping on MC-OWC device performance using a combined numerical and experimental approach.

The research methodology was based on two series of experimental sessions and two numerical models. The first experimental campaign was conducted in a small wave flume in the University of Technology Sydney (UTS) for a MC-OWC device at a model-scale of 1:25. This experiment was performed mainly to validate the numerical models and initially observe device response when subjected to limited regular wave conditions. The second experimental session was carried out in the wave flume at the Manly Hydraulic Laboratory (MHL) in New South Wales, Australia for a MC-OWC devices at a model-scale of 1:16. This experiment was designed to 1) assess the device performance over a wide range of regular and irregular wave conditions, 2) study the impact of wave height, wave period and device draught on the performance of a MC-OWC device, and 3) investigate the effect of the pneumatic damping induced by the power take-off (PTO) system on device performance.

The first validated numerical model was a MATLAB time-domain model that was based on a coupling between the rigid piston model and the thermodynamic forces on a MC-OWC device to get a preliminary understanding of device performance. The second numerical model was a fully nonlinear 3D Computational Fluid Dynamics

(CFD) model that was constructed using the commercial code STAR-CCM+. After being validated in good agreement against the physical scale model tests, the CFD model was utilised to study the influence of the power take-off (PTO) damping on the water surface elevation inside the chamber, the differential air pressure, the airflow rate and the device capture width ratio under different incident regular wave conditions.

The extensive analysis of 198 physical tests and 84 CFD simulations revealed that the water surface elevation, differential air pressure, and airflow rate had a similar response in all chambers to the wave conditions, device draught and PTO damping. However, the first chamber always played the primary role in wave energy extraction, and the performance gradually decreased down to the fourth chamber where the lowest performance was found. The maximum capture width ratio of the whole MC-OWC device was found to be 2.1 under regular wave conditions and 0.95 under irregular wave conditions. These ratios were the highest among all similar concepts that have been reported in previous research.

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## Acronyms and Abbreviations

### Notations

$A_1$	Chamber area	(m <sup>2</sup> )
$A_2$	Orifice opening area	(m <sup>2</sup> )
$a$	Wave amplitude	(m)
$B$	Hydrodynamic damping coefficient	(Ns m <sup>-1</sup> )
$C_d$	Coefficient of discharge	(–)
$C_g$	Group velocity	(m s <sup>-1</sup> )
$c$	Wave velocity	(m s <sup>-1</sup> )
$c_s$	Speed of sound	(m s <sup>-1</sup> )
$D$	Orifice diameter	(m)
$D_{\text{pipe}}$	Internal diameter of the pipe	(m)
$d$	Draught of the water column	(m)
$d'$	The added draught due to added mass	(m)
$E$	Total energy	(J)
$E_k$	Kinetic energy	(J)
$E_p$	Potential energy	(J)
$F$	Force	(N)
$F_a$	Added mass force	(N)
$F_{\Delta p}$	Force due to the varying air pressure	(N)
$F_{FK}$	Froude–Krylov force	(N)
$F_d$	Damping force	(N)
$F_{\text{ex}}$	Exciting force (heave mode)	(N)
$f$	Frequency	(Hz)
$f_e$	Peak frequency	(Hz)
$fn$	Natural frequency	(Hz)
$\Delta f$	Frequency bands width	(Hz)
$Gi$	The wave sensors	(–)
$G_{in}$	The incident wave height sensor ( in the front of the device)	(–)
$G_{out}$	The wave height sensor in the device rear	(–)
$g$	Acceleration due to gravity	(m s <sup>-2</sup> )
$H$	Wave height	(m)
$H_s$	Significant wave height	(m)
$h$	Water depth	(m)
$h_{in}$	The height of the top cover of the chamber relative to the water surface level inside the chamber	(m)

$h_{a0}$	The height of the top cover of the chamber relative to the SWL	(m)
$K$	Hydrostatic restoring coefficient	(N m <sup>-1</sup> )
$k$	Wavenumber	(m <sup>-1</sup> )
$k_c$	The coverage factor	(–)
$L$	Wave length	(m)
$L_C$	Chamber length	(m)
$l$	Length scale	(–)
$M$	Mass of the column of water	(kg)
$M_a$	Added mass (heave mode)	(kg)
$m$	Air mass	(kg)
$\dot{m}$	Mass flow rate	(kg s <sup>-1</sup> )
$N$	Number of calibration sample	(–)
$n$	Number of repeated observations	(–)
$P_n$	Pneumatic power	(W)
$\bar{P}_n$	Time-averaged pneumatic power	(W)
$P_{in}$	Mean incident power per meter of the wave crest	(W m <sup>-1</sup> )
$P_w$	Input power in the OWC	(W)
$P_t$	The power due to pressure	(W)
$P_a$	The power is due to airflow velocity	(W)
$p_c$	Pressure inside a chamber	(Pa)
$p_{atm}$	Atmospheric air pressure at standard temperature and pressure	(Pa)
$\Delta p$	Differential air pressure ( $p - p_{atm}$ )	(Pa)
$p_{wave}$	Dynamic pressure field	(Pa)
$Q_w$	Airflow rate	(m <sup>3</sup> s <sup>-1</sup> )
$Q_p$	Volumetric airflow	(m <sup>3</sup> s <sup>-1</sup> )
$\dot{R}$	The ideal gas constant which is equal to 287.1 for dry air	(J kg <sup>-1</sup> K <sup>-1</sup> )
$Ri$	Opening ratio	(–)
$R$	Correlation coefficient	(–)
$\dot{R}$	Ideal gas constant	(J kg <sup>-1</sup> K <sup>-1</sup> )
$S(\omega)$	Spectral variance density	(–)
$S$	Standard deviation	(–)
$s$	Wave steepness	(–)
$t$	Time	(s)
$\Delta t$	Time step	(s)

$T$	Wave period	(s)
$T_R$	Resonant period	(s)
$T_p$	Peak period	(s)
$T_k$	The ambient temperature is in Kelvin	(K)
$T_c$	The chamber temperature is in Kelvin	(K)
$U_S$	Standard uncertainty	(–)
$U_{S-A}$	Standard uncertainty Type A	(–)
$U_{S-B}$	Standard uncertainty Type B	(–)
$V$	Air volume	(m <sup>3</sup> )
$V_i$	Air flow velocity	(m. s <sup>-1</sup> )
$Y_i$	The calibrated data	(–)
$\dot{Y}_i$	The fitted value	(–)
$z$	The vertical co-ordinate	(m)
$u$	Fluid velocity in the x-direction	(m s <sup>-1</sup> )
$v$	Fluid velocity in the y-direction	(m s <sup>-1</sup> )
$w$	Fluid velocity in the z-direction	(m s <sup>-1</sup> )
$\eta$	Water surface elevation	(m)
$\varepsilon$	Capture width ratio	(–)
$\varepsilon_c$	Chamber capture width ratio	(–)
$\phi$	Velocity potential	(m <sup>2</sup> s <sup>-1</sup> )
$\tau$	Damping coefficient	( kg <sup>1/2</sup> m <sup>-7/2</sup> )
$\gamma$	The heat capacity ratio	(–)
$\delta$	Calibration factor	(–)
$\rho_w$	Water density (= 998.2 at 293 K )	( kg m <sup>-3</sup> )
$\rho_{air}$	Air density (=1.2 for dry air at 293 K)	( kg m <sup>-3</sup> )
$\theta$	Angular length of the chamber	(rad)
$\omega$	Angular frequency	(s <sup>-1</sup> )
$\omega_n$	Natural frequency	(rad s <sup>-1</sup> )
$\Gamma$	Viscous stress tensor	(–)
$\alpha$	Constant that relates to the wind speed and fetches length	(–)
$\beta$	Pipe diameter ratio	(–)
$\Upsilon$	Peak enhancement	(–)
$\sigma$	Spectral shape factor	(–)
$\sigma_{est}$	The standard error of the estimate	(–)
$\mu$	Dynamic viscosity	(m <sup>2</sup> s <sup>-1</sup> )
$\lambda$	Scale ratio	(–)

### **Abbreviations Used in Thesis**

BEM	Boundary element method
CFD	Computational Fluid Dynamics
Ch-1	The first chamber (face the incoming wave)
Ch-2	The second chamber
Ch-3	The third chamber
Ch-4	The fourth chamber
FVM	Finite Volume Method
HRIC	High-Resolution Interface Capturing
LWT	Linear wave theory
MC-OWC	Multi-chamber oscillating water column
MHL	Manly Hydraulic Laboratories
NWT	Numerical wave tank
NRMSE	Normalized Root Mean Square Error
OWC	Oscillating water column
PTO	Power take-off
RANS	Reynolds-Averaged Navier-Stokes
SST	Shear stress transport
SWL	Still water level
UTS	University of Technology Sydney
VOF	Volume of Fluid
WEC	Wave energy converter