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

MOHAMMAD MOUSA ODEH SHALBY

Faculty of Engineering & Information Technology
School of Mechanical and Mechatronics Engineering

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

Done by: MOHAMMAD MOUSA ODEH SHALBY

Supervisor: Dr. Paul Walker
Co–supervisor: Dr. Phuoc Huynh
External supervisor: Prof. David Dorrell
External supervisor: Dr. Ahmed Elhanafi

Course code: C02018

Subject Number: 49986 Doctor of Philosophy (PhD)

Dates: 24/02/2015 to 18/02/2018

University of Technology Sydney (UTS)

P.O. Box 123, Broadway, Ultimo, N.S.W. 2007

Australia

Certificate

I certify that the work in this thesis has not previously been submitted for a degree nor has it been submitted as part of requirements for a degree except as part of the collaborative doctoral degree and/or fully acknowledged within the text.

I also certify that the thesis has been written by me. Any help that I have received in my research work and the preparation of the thesis itself has been acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis. This research is supported by the Australian Government Research Training Program.

Signature of Student:

Production Note:
Signature removed prior to publication.

Date: *18 February 2019*

Acknowledgements

First and foremost, my sincere thanks go to Allah, who endowed me to complete this doctorate and for creating the grand power of ocean waves I have had the honour of studying in such depth. In particular, I am grateful to AL–Hussein bin Talal University, Ma'an, Jordan for their financial support of this project.

Most of all, I wish to thank my supervisory team, Dr.Paul Walker, Dr Phuoc Huynh and Professor David Dorrell for giving me the opportunity to perform this work and having guided and helped me throughout the project. Their assistance and advice have made this a rewarding experience. I would also like to extend my sincere gratitude to Dr. Ahmed Elhanafi for his dedicated help, expertise, advice, inspiration, encouragement and continuous support, throughout my studies.

I express my thanks to Manly Hydraulic Laboratories for allowing me to use their laboratory facilities for my experimental work and I would like to acknowledge Mr. Indra Jayewardene and other staff in Manly Hydraulic Laboratories for their assistance during my research. I offer my thanks to Mr.Christopher Hamid, Mr. Michael Diponio andEng.Vahik Avakian from the School of Mechanical and Mechatronic Engineering for their cooperation, encouragement and for facilitating the requirements for this research work.

I am extremely grateful to my mother, father, brothers and sisters for all of the sacrifices that you've made on my behalf. Your prayers for me have sustained me thus far. I will never be able to pay back the love and affection showered upon me by my family. I especially wish to thank my wife, Hafsa, who has been extremely supportive of me throughout this entire process and has made countless sacrifices to help me get to this point.

Finally, I would like to give my special thanks to my great friends. Their motivation and continuous support have helped make this project happen and a more than enjoyable experience. I am really very grateful for all you have done for me.

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.

Table of Contents

List of Figures

List of Tables

Acronyms and Abbreviations

Notations

A_1	Chamber area	(m^2)
A_2	Orifice opining area	(m^2)
a	Wave amplitude	(m)
B	Hydrodynamic damping coefficient	(Ns m^{-1})
C_d	Coefficient of discharge	(–)
C_g	Group velocity	(m s^{-1})
c	Wave velocity	(m s^{-1})
c_s	Speed of sound	(m s^{-1})
D	Orifice diameter	(m)
D_{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_{ex}	Exciting force (heave mode)	(N)
f	Frequency	(Hz)
f_e	Peak frequency	(Hz)
fn	Natural frequency	(Hz)
Δf	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^{-2})
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^{-1})
k	Wavenumber	(m^{-1})
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^{-1})
N	Number of calibration sample	(–)
n	Number of repeated observations	(–)
P_n	Pneumatic power	(W)
$\overline{P}_n$	Time–averaged pneumatic power	(W)
P_{in}	Mean incident power per meter of the wave crest	(W m^{-1})
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)
Δp	Differential air pressure ($p - p_{\text{atm}}$)	(Pa)
p_{wave}	Dynamic pressure field	(Pa)
Q_w	Airflow rate	(m^3 s^{-1})
Q_p	Volumetric airflow	(m^3 s^{-1})
$\dot{\text{R}}$	The ideal gas constant which is equal to 287.1 for dry air	(J kg^{-1} K^{-1})
Ri	Opening ratio	(–)
R	Correlation coefficient	(–)
$\dot{\text{R}}$	Ideal gas constant	(J kg^{-1} K^{-1})
$S(\omega)$	Spectral variance density	(–)
S	Standard deviation	(–)
s	Wave steepness	(–)
t	Time	(s)
Δt	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	(–)
$U_{S\text{-}A}$	Standard uncertainty Type A	(–)
$U_{S\text{-}A}$	Standard uncertainty Type B	(–)
V	Air volume	(m^3)
V_i	Air flow velocity	(m. s^{-1})
Y_i	The calibrated data	(–)
$\grave{Y}_i$	The fitted value	(–)
z	The vertical co–ordinate	(m)
u	Fluid velocity in the x–direction	(m s^{-1})
v	Fluid velocity in the y–direction	(m s^{-1})
w	Fluid velocity in the z–direction	(m s^{-1})
η	Water surface elevation	(m)
ε	Capture width ratio	(–)
ε_c	Chamber capture width ratio	(–)
ϕ	Velocity potential	(m^2 s^{-1})
τ	Damping coefficient	(kg$^{1/2}$ m$^{-7/2}$)
γ	The heat capacity ratio	(–)
δ	Calibration factor	(–)
ρ_w	Water density (= 998.2 at 293 K)	(kg m^{-3})
ρ_{air}	Air density (=1.2 for dry air at 293 K)	(kg m^{-3})
θ	Angular length of the chamber	(rad)
ω	Angular frequency	(s^{-1})
ω_n	Natural frequency	(rad s^{-1})
Γ	Viscous stress tensor	(–)
α	Constant that relates to the wind speed and fetches length	(–)
β	Pipe diameter ratio	(–)
Υ	Peak enhancement	(–)
σ	Spectral shape factor	(–)
σ_{est}	The standard error of the estimate	(–)
μ	Dynamic viscosity	(m^2 s^{-1})
λ	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 Sydeny
VOF	Volume of Fluid
WEC	Wave energy converter