HYBRID BACKWARD BENT DUCT BUOY AND POINT ABSORBER WAVE ENERGY CONVERTER FOR LOW WAVE HEIGHT

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DOCTOR OF PHILOSOPHY (MECHANICAL ENGINEERING)

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ABSTRACT

Recently, most Wave Energy Converter (WEC) was designed to harvest energy from high wave height conditions, which had less efficiency for low wave height conditions. This weakness causes difficulties for countries with a high potential to utilise ocean energy, such as Malaysia. Furthermore, research on suitable designs to harness highly efficient energy from low wave heights is lacking. Therefore, this study aims to determine the optimum condition parameters for a WEC to provide the best performance in low wave height. Its main objective is to investigate the hydrodynamic characteristics of a hybrid WEC by applying a new form of hybrid Backward Bent Duct Buoy (BBDB) and Point Absorber (PA) at low wave height. To overcome the weakness of BBDB and PA as well as to solve precision methods for investigating the performance of the results, the effects of single BBDB, PA, and a new hybrid form of BBDB-PA on heave Response Amplitude Operator (RAO) and power absorption were examined within various ranges of wave periods under regular wave conditions using ANSYS Advanced Quantitative Wave Analysis (AQWA) is examined. The results revealed that the new hybrid form significantly influenced the hydrodynamic characteristics like excitation force, radiation damping coefficient, and added mass of the BBDB and PA. This form also has a peak of heave RAOs and power absorption occurring in T = 1.2 s, with a value around 1.5 - 3 and 6 kW -16 kW, respectively. Besides, this research also optimises the position of PA, gap length between BBDB and PA, and diameter of PA of hybrid WEC and performs an empirical model at low wave height. The optimisation process was applied based on the data collected over one year about sea characteristics for a nearshore region of Mantanani Island. Note that this research presents a methodology for optimising the hybrid BBDB-PA based on statistical analysis and hydrodynamics of the system in frequency and performing empirical model. The optimum parameter was selected for front position PA with a 5 m diameter and 7 m gap length with BBDB for the Mantanani Island wave characteristics. To validate the empirical model of response amplitude operator for hybrid WEC at low wave height using an experiment, it was verified with an experimental scale model of 1:30 in a 2D wave flume with a wave height of 0.5 m and a wave period of 1 s -1.5 s. The hybrid BBDB and PA yielded higher performance at T = 1.25 s, with a value of 4 and 8, respectively, compared to the single BBDB and PA. Despite the condition parameter, it was discovered that the WEC position and arrangement were responsible for the highest power value regardless of the PA position used in the experiment. The results offer recommendations for optimising the design of hybrid WECs and imply the possibility of synergy between BBDB and PA to fully utilise ocean space for energy.

ABSTRAK

Sedasawarsa ini, kebanyakan WEC telah direka untuk menuai tenaga daripada keadaan ketinggian ombak tinggi, yang mempunyai kecekapan yang kurang untuk keadaan ketinggian ombak rendah. Kelemahan ini menyebabkan kesukaran kepada negara yang berpotensi tinggi dalam memanfaatkan tenaga lautan seperti Malaysia. Tambahan pula, terdapat kekurangan penyelidikan mengenai reka bentuk yang sesuai untuk memanfaatkan tenaga yang sangat cekap dari ketinggian ombak rendah. Oleh itu, kajian ini bertujuan untuk menentukan parameter optimum untuk penukar tenaga ombak bagi memberikan prestasi terbaik dalam ketinggian ombak rendah. Objektif utamanya adalah untuk menyiasat ciri-ciri hidrodinamik penukar tenaga ombak hibrid dengan menggunakan bentuk baharu *Backward Bent Duct Buoy (BBDB)* dan *Point Absorber (PA)* hibrid pada ketinggian ombak rendah. Bagi mengatasi kelemahan BBDB dan PA serta untuk menyelesaikan kaedah yang tepat untuk menyiasat prestasi keputusan, kesan BBDB tunggal, PA dan bentuk hibrid baharu BBDB-PA pada *Heave Response Amplitude Operator (RAO)* dan penyerapan kuasa telah diperiksa dalam pelbagai julat tempoh ombak di bawah keadaan ombak biasa menggunakan ANSYS-AQWA. Hasilnya menunjukkan bahawa ciri-ciri hidrodinamik seperti *excitation force, radiation damping coefficient*, dan *added mass* bagi BBDB dan PA dipengaruhi dengan ketara oleh bentuk hibrid baharu. Bentuk ini juga mempunyai kemuncak *heave* RAOs dan penyerapan kuasa yang berlaku dalam T = 1.2 s, dengan nilai sekitar 1.5 - 3 dan 6 kW - 16 kW, masing-masing. Selain itu, kajian ini juga mengoptimumkan kedudukan PA, panjang jarak antara BBDB dan PA, dan diameter PA WEC hibrid dan melakukan model empirikal pada ketinggian ombak rendah. Proses pengoptimuman telah digunakan berdasarkan data yang dikumpul selama satu

tahun tentang ciri-ciri laut untuk kawasan berhampiran pantai Pulau Mantanani. Penyelidikan ini membentangkan metodologi untuk mengoptimumkan BBDB-PA hibrid berdasarkan analisis statistik dan hidrodinamik sistem dalam kekerapan dan melaksanakan model empirikal. Parameter optimum dipilih untuk PA kedudukan hadapan dengan diameter 5 m dan panjang jarak 7 m dengan BBDB bagi ciri ombak Pulau Mantanani. Untuk mengesahkan model empirikal RAO untuk WEC hibrid pada ketinggian ombak rendah menggunakan eksperimen, model empirikal telah disahkan dengan model skala eksperimen 1:30 dalam tanki ombak 2D dengan ketinggian ombak 0.5 m dan tempoh ombak 1s -1.5s. BBDB hibrid dan PA menghasilkan prestasi yang lebih tinggi pada T = 1.25 s, dengan nilai 4 dan 8, masing-masing; berbanding dengan BBDB dan PA tunggal. Selain keadaan parameter, didapati bahawa kedudukan dan susunan WEC juga memberi kesan untuk nilai kuasa tertinggi tanpa mengira kedudukan PA yang digunakan dalam eksperimen. Hasilnya menawarkan cadangan untuk mengoptimumkan reka bentuk WEC hibrid dan membayangkan kemungkinan sinergi antara BBDB dan PA untuk menggunakan sepenuhnya ruang lautan untuk tenaga.

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The Examination Committee has met on **27th September 2023** to conduct the final examination of **Muhamad Aiman bin Jalani** on his degree thesis entitled **'Hybrid Backward Bent Duct Buoy and Point Absorber Wave Energy Converter for Low Wave Height'**.

The committee recommends that the student be awarded the **Doctor of Philosophy (Mechanical Engineering).**

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Academic session	: 2021/2022

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LIST OF ABBREVIATIONS

BBDB	Backward Bent Duct Buoy
PA	Point Absorber
RAO	Response Amplitude Operator
WEC	Wave Energy Converter
RE	Renewable Energy
OWC	Oscillating Water Column
PTO	Power Take-Off
PV	Solar Photovoltaic
MW	Mega Watt
CFD	Computational Fluids Dynamic
PFT	Potential Flow Theory
CO_2	Carbon Dioxide
IEA	International Energy Agency
OES TCP	Ocean Energy System Technology Collaboration Program
TWh	Tera Watt hour
OTEC	Ocean Thermal Energy Conversion
MWh	Mega Watt hour
DTN	*Dasar Tenaga Nasional*
GW	Giga Watt
USA	United States America
DoF	Degrees of Freedom
EMEC	European Marine Energy Centre
AWS	Archimedes Wave Swing
OWCOB	Oscillating Water Column Oscillating Buoy
OWT	Offshore Wind Turbine
FABWEC	Floating Array Buoys Wave Energy Conversion
AQWA	Advanced Quantitative Wave Analysis
BEM	Boundary Element Method
DOE	Design Of Experiment
kW	Kilo Watt

λ	Length Of Wave
k	Wave Number
ω	Angular Velocity
d	Water Depth
T	Wave Period
M	Mass
z	Vertical Displacement
F_e	Force Excitation
F_r	Force Radiation
F_h	Force Hydrostatic
F_{drag}	Force Drag
F_{ext}	Force External
F_{pto}	Force PTO
F_{FK}	Force Froude-Krylov
F_d	Force Diffraction
C	Radiation Damping
Fd	Morrison Drag Force
Cd	Drag Coefficient
μ	Flow Velocity
H	Wave Height
ρ	Water Density
g	Gravity
K	Hydrostatic Stiffness
B_{PTO}	PTO damping coefficient
q_{iws}	Airflow driven by the Internal Water Surface
P_{reg}	Power in Regular Wave
WG	Wave Gauge
CAD	Computer-Aided Design
2D	Two Dimension
3D	Three Dimension
KeTSA	*Kementerian Tenaga dan Sumber Asli*
RSM	Response Surface Method
GPS	Global Positioning System
L	Length of gap between BBDB and PA

m	Metre
D	Diameter of PA
s	Second
ADCP	Acoustic Doppler Current Profiler
IMU	Inertial Measurement Unit
UPNM	Universiti Pertahanan Nasional Malaysia

CHAPTER 1

INTRODUCTION

1.1 Background Research

Nowadays, in the era of the industrial revolution in the eighteenth century, humans began to explore further and develop towards more sophisticated technological advances. Development in science and technology is increasing rapidly. Hence, society's demand for energy has increased in terms of energy consumption, especially fossil fuels. Fossil fuel combustion emits large amounts of toxic gases and produces a greenhouse effect, leading to global anomalous climate and extreme weather changes [1].

Climate change has caused energy shortages and the greenhouse effect in recent years, alarming many countries to opt for a full range of alternative energy solutions [2]. Some countries conducted studies and developed a variety of alternative energy that can reduce carbon and cost to reduce fossil fuel energy. Renewable Energy (RE) is the most promising alternative energy, including solar, wind, geothermal, biomass, and ocean energy. However, widely used RE sources such as wind and solar have low energy density and poor stability due to their dependence on a seasonal basis [3]. Therefore, due to the advantages of wave energy and its status as one of the most dense, predictable, and persistent energy sources, this wave energy is the main focus of this study [4].

1.1.1 Wave Energy Potential in Malaysia

Malaysia is among the countries with high potential in utilising ocean energy for electricity as it has a vast coastline along the South China Sea and the Straits of Malacca, with a length of 4,675 km [5]. Malaysia also has strong seasonal monsoon blows, causing it to always have turbulent waves in its surrounding sea and some areas [6]. Hence, properly using the geographical advantage of Malaysia, which is surrounded by the sea, development, and research on ocean utilisation, will contribute greatly and solve the problems of difficult energy consumption in Malaysia.

Malaysia's government has established many energy policies, as well as monetary support for RE research and development, particularly in local institutions, to reduce the country's reliance on fossil fuels [7]. Since the Malaysian government's encouragement of RE in the 11th Malaysian Plan [8], only 8% of Malaysia's energy is currently generated from RE, despite the country's pledge to increase that percentage to 20% by 2025 [9]. Therefore, Malaysia's government has been exploring high-potential, nascent new energy sources such as geothermal, wind, solar thermal, and ocean, as stated in National Energy Policies 2022-2040 [10]. Nevertheless, the major challenge faced by the RE industry in Malaysia is the intermittency problem in energy production, particularly solar energy. Malaysia only receives an average of 6 hours of direct sunlight for electricity generation during the day, provided that it is not raining and many sun rays are not reflected. The average monthly solar radiation is approximately 400 MJ/m^2 [11]. Wind energy is also restricted by low wind velocity (less than 2 m/s), blows irregularly, and is not only weather dependent [12] but also has a weak ecosystem and low biodiversity [13].

Wave energy has a substantially higher intensity than other RE sources like wind and solar [14]. Nonetheless, there are limitless waves along the coastline, whether during the day or night. In addition, Kai et al. researched the current status of marine RE in Malaysia and its challenges [5]. The authors concluded that this energy is the best alternative to electricity and can also contribute to the energy-balancing market in Malaysia. Note that the coastal regions in Malaysia are accessible to low wave power with an optimum annual power of 8.5 kW/m yearly, except for the east coast of Peninsular Malaysia during the monsoon season [15]. However, the ideal wave power density for WEC to generate enough power and be commercially viable should be more than 50 kW/m [5]. This energy will become important when variable RE becomes a larger part of the energy mix. Due to its continuous supply, Malaysia has a great opportunity to convert wave energy into electrical energy. Aside from that, it can be regarded as a low-cost, environmentally friendly RE source capable of reducing reliance on fossil fuels for electricity generation.

1.1.2 Wave Energy Converter

Wave Energy Converter (WEC) devices can be divided into three types, namely, Oscillating Water Column (OWC), wave-activated bodies, and overtopping bodies [16]. OWC WECs are among the most promising types [17] compared to the other two types in terms of their mechanical and structural simplicity, accessibility, and reliability [18]. Other than that, OWC devices are relatively simple in design and have no underwater moving parts. This simplicity can lead to higher reliability and lower maintenance requirements compared to more complex and moving parts like oscillating bodies and overtopping devices.

One of the most successful OWC types [19], called a Backward Bent Duct Buoy (BBDB), is a simple floating structure WEC concept [20], [21] and is cost-efficient compared to other WECs [22]. Note that the BBDB is a floating OWC proposed by Masuda and Yamazaki [23]. For wave-activated bodies type of WECs, the Point Absorber (PA) is a WEC that takes advantage of the ocean waves' oscillatory up and down heave movement [24]. PAs are also one of the most common devices that typically have a floater moving in an oscillating, heaving, and pitching motion turned into electricity by a Power Take-Off (PTO) system [25]. This non-directional device absorbs energy from all directions by moving at or near the water's surface. Owing to their simplicity, PAs are more durable than other wave energy devices in harsh wave conditions [26].

1.2 Problem Statement

Although the ocean surrounds Malaysia, taking advantage of its energy is challenging due to the wave conditions. Compared to other countries, Malaysia has a relatively low energy wave characteristic. Malaysian seas have a low climate, with significant wave heights ranging between 0.5 and 1.5 m and peak periods ranging between 5 s and 7 s. Due to Sumatera's protection, the west coast of peninsular Malaysia, Malacca