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Design of oscillating-water-column wave energy converters with an application to self-powered sensor buoys

J.C.C. Henriques*, J.C.C. Portillo, L.M.C. Gato, R.P.F. Gomes, D.N. Ferreira, A.F.O. Falcão

LAETA, IDMEC, Instituto Superior Técnico, Universidade de Lisboa, Av. Rovisco Pais, 1049-001 Lisboa, Portugal

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ABSTRACT

The quest for conquering the ocean and understanding its behaviour has been a challenge with increasing needs for innovation and technology investments in many areas of strategic value for the promotion, growth and competitiveness of the marine economy worldwide. Current oceanographic buoy systems are limited to low power levels and intermittency of data acquisition and transmission, among other aspects that need to be overcome to comply with new and more demanding applications. The development of marine activities requires more powerful and reliable data-acquisition systems to guarantee their future sustainability. This work presents a new systematic methodology for optimum design of wave energy converters. The methodology was applied to design two self-powered sensor buoys for long term monitoring based on the oscillating-water-column principle. The optimisation focussed on buoy hydrodynamic shape, sizing and selection of the turbine and the generator, as well as the control law of the generator electromagnetic torque. The performance was assessed through the use of the power matrix and a set of performance indicators. These performance indicators were defined to allow a simple comparison between different wave energy concepts. The results confirm the applicability of the designed buoys for a next generation of oceanographic monitoring systems.

1. Introduction

The overall demand for energy and associated services to meet social and economic development has become one of the most challenging problems of the global economy. The increase in the penetration of renewable energy in the energy mix has driven great efforts of R&D in the last decades, especially in the European Union (EU) [1,2], which has set up ambitious goals for the coming years.

The European Commission has established a series of initiatives based on the Marine Strategy Framework Directive for promoting the marine knowledge and seabed mapping. It has been estimated that high-quality marine data widely available in the EU would improve productivity by over €1 billion per year [3]. This sets urgent areas of development for better and long-lasting ocean observing systems. Reducing the costs for data acquisition is therefore a key priority in the EU. In this context, it is fundamental to develop cost-effective and multi-functional platforms, including sensors, to perform long-term monitoring and provide reliable *in situ* measurements of key parameters. The solution to this problem must take advantage of a new generation of technologies involving several domains of knowledge, such as: energy conversion and storage; data acquisition, pre-processing, storage and transmission; miniaturisation; communication; disposable non-pollutant technologies and standardisation.

The current capabilities of monitoring buoys are still quite limited by their energy source. That is, the existing sensor buoy power systems often include photovoltaic panels and batteries whose lifetime and power output are insufficient for modern applications [4]. Some sensor buoys are even designed to sink after exceeding the battery life because recharging is impractical or too costly, thus contributing to environmental and economical impacts [5].

The marine economy is driving ambitious projects for data-acquisition systems, which may involve sea-charging floating stations for autonomous underwater vehicles (AUVs) [6] and long-term deep ocean autonomous scientific observation systems [7]. Harnessing ocean wave energy with a reliable and self-sufficient system is an appealing concept for the electricity supply of on-

* Corresponding author.
E-mail addresses: joaochenriques@tecnico.ulisboa.pt (J.C.C. Henriques), juan.portillo@tecnico.ulisboa.pt (J.C.C. Portillo), luis.gato@tecnico.ulisboa.pt (L.M.C. Gato), ruigomes@tecnico.ulisboa.pt (R.P.F. Gomes), nevesferreira@tecnico.ulisboa.pt (D.N. Ferreira), antonio.falcao@tecnico.ulisboa.pt (A.F.O. Falcão).

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Nomenclature

Romans

a	generator control law constant (19)
$\mathbf{A}_{ij}$	state matrix of the radiation R_{ij} state-space representation (6) [s^{-1}]
A_{ij}^{∞}	limiting value at infinite frequency of the added mass of body i as affected by body j motion [kg]
A_{ω}	wave amplitude (3) [m]
b	generator control law exponent (19)
$\mathbf{b}_{ij}$	input matrix of the radiation R_{ij} state-space representation (6) [m^{-1}]
$\mathbf{c}_{ij}$	output matrix of the radiation R_{ij} state-space representation (6) [N]
d_1	buoys outer diameter, see Figs. 7 and 11 [m]
d_2	buoys inner diameter, see Figs. 7 and 11 [m]
d	turbine rotor diameter [m]
E_{abs}	annual absorbed energy [kWh]
F_{di}	excitation force on body i (3) [N]
g	acceleration of gravity [m/s^2]
h	vertical length, see Figs. 7 and 11 [m]
H_s	significant wave height [m]
I	turbine/generator set moment of inertia [kg m^2]
m_i	mass of body i [kg]
$\dot{m}_{turb}$	turbine mass flow rate [kg/s]
p	absolute air chamber pressure [Pa]
p^*	dimensionless relative pressure (2) [−]
P_{abs}	absorbed power [W]
p_{at}	absolute atmospheric pressure [Pa]
P_{elect}	electrical power (21) [W]
P_{gen}^{em}	generator electromagnetic power (20) [W]
P_{gen}^{opt}	optimal generator power (19) [W]
P_{gen}^{rated}	generator rated power [W]
P_{turb}	turbine aerodynamic power (13) [W]
Q_{turb}	turbine volumetric flow rate [m^3/s]
R_{ij}	radiation damping forces on body i due to body j (6) [N]
S_1	floater water plane area [m^2]
S_2	OWC water plane area [m^2]
t	time [s]
t_{year}	annual operational time [h]
T_e	energy period [s]
T_{gen}^{em}	generator electromagnetic torque (23) [N m]
T_{turb}	turbine aerodynamic torque (17) [N m]
V_0	volume of air inside the chamber in calm water [m^3]
V_c	instantaneous air chamber volume [m^3]
v_i	velocity of body i [m/s]
$\mathbf{x}$	system state (24)
x_i	vertical position body i [m]
$\mathbf{X}_1$	Fast Fourier Transform of $\mathbf{x}_1$ [m s]
$\mathbf{y}_{ij}$	radiation state R_{ij} (5) [−]

Greek symbols

β	constant (10) [−]
γ	specific heat ratio of air, C_p/C_v [−]
Γ_i	excitation force of body i per unit wave height [N/m]
Δt	time interval used to discretize the ODE system (24) [s]
η_{turb}	turbine efficiency (14) [−]
η_{gen}	generator efficiency, Fig. 6b unit wave amplitude (3) [−]
κ	polytropic exponent (18) [−]
Λ_{gen}	generator load (22) [−]
Π	turbine dimensionless power (13) [−]
Π_d	displacement per unit of significant wave height (33) [−]
Π_{EV}	annual absorbed energy per unit of submerged volume (32) [kWh/m^3]
Π_F	absorbed power per unit of linear velocity of the PTO (29) [N]
ϱ	air density [kg/m^3]
ϱ_{at}	air density at atmospheric conditions [kg/m^3]
ϱ_{in}	stagnation air density at turbine inlet (15) [kg/m^3]
ϱ_w	water density [kg/m^3]
Φ	turbine dimensionless flow rate (12) [−]
ϕ_i	phase of body i response (3) [rad]
Ψ	turbine dimensionless pressure head (11) [−]
ω	wave frequency (3) [rad/s]
Ω	turbine/generator set rotational speed [rad/s]

Superscripts

*	dimensionless quantity
em	electromagnetic quantity
opt	optimal value
rated	rated quantity
rms	root-mean-square
T	transpose operator

Subscripts

1	buoy, denoted as body 1 in (1)
2	weightless rigid piston, denoted as body 2 in (1)
at	atmospheric quantity
c	chamber
elect	electrical quantity
gen	generator quantity
in	turbine inlet conditions
max	maximum value
n	sea state
turb	turbine quantity

board sensors. In particular, the recent development of self-powered buoys equipped with data acquisition sensors suggests a novel way to use moored buoys to extract energy from waves, while providing continuous real-time data measurements for ocean monitoring. The MBARI's Wave-Power Buoy is one of the prototypes designed to fulfil such roles [8,9].

The concept of harvesting wave energy for powering small buoys is not new. Yoshio Masuda (1925–2009) was the first to develop navigation buoys powered by wave energy [10]. The device is basically a floater rigidly pierced by a vertical tube, see Fig. 1a. The upper part, above the water line, forms an air chamber open to the atmosphere through a duct where an air turbine is installed. Wave action alternately compresses and decompresses the trapped air which forces air to flow through the turbine [11]. Masuda's systems were later known as floating oscillating-water-column devices (OWCs). The original Masuda's buoys used conventional unidirectional turbines instead of self-rectifying (bidirectional) air turbines. This required rectifying valves which affected the energy conversion efficiency (see Fig. 1b). Due to their inherent simplicity and reliability, more than one thousand of these navigation buoys were deployed in Japan, China and USA [10,12]. Remarkably, several of these buoys were fully operational for more than three decades.