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Analytical study of the interaction between waves and cylindrical wave energy converters oscillating in two modes

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ABSTRACT

Ocean wave energy may be recovered by oscillating wave energy converters. The energy converter studied in this work is a horizontally orientated cylinder which can be placed at different depths in the sea. The cylinder can oscillate in horizontal and vertical directions and transfer mechanical energy forward by hydraulic cylinders. To study the interaction between the waves and the converter, we have used potential flow theory separately for both the waves and the oscillating cylinder, and then combined these potential functions by using the principle of superposition. Combined potential flow fields, together with Euler's equations, enable us to obtain the pressure distribution around the cylinder. When knowing the pressure distribution, both the force upon the cylinder, and the net mechanical power transferred from the waves to the moving cylinder, can be calculated. With this model we have analyzed several interesting topics which affect the efficiency of the wave energy converter. The phase shift is the most important parameter – with the phase shift $-\pi/2$ the best efficiency 0.5 was achieved. To achieve the right phase shift for different waves is essential due to the power capture. Furthermore, it is shown that feedback control is necessary for keeping the phase shift constant. Also the cylinder radius has a great effect on the efficiency. The other important parameters studied in this work were the wave height and the wave period.

1. Introduction

Wave energy is still on the pre-commercial stage even though ocean waves have a huge energy potential around the world. The growth rate of ocean energy sector, including wave energy, is predicted to be over twenty years behind the growth rate of the onshore wind energy sector and the real expansion is assumed to begin around 2030 [1].

Ocean waves have significantly high power densities in comparison with solar and wind energy. The circumstances vary around the world and are very site-specific. The greatest power densities are in Europe, North America, southernmost America and South Australia [2]. Wave energy has been designed to be harnessed with a great number of different types of wave energy converters. No single technology has yet managed to beat the others. The converters can be categorized using their location or principle of operation. Some converters, like oscillating water columns and overtopping devices, have no moving parts except turbines or motors and are situated on the coastline. In oscillating water columns, water flows to the chamber during the wave and forces air to flow through turbines. In overtopping devices, water rises over the edge of the tank during the wave and flows through the hydraulic turbine.

The operation of several wave energy devices is based on moving parts which are connected to the parts fixed for instance at the bottom of the sea. These devices utilize the elliptical movement of water particles during the wave. The orbits are round offshore and become more elliptical near the shore. Waves running on the beach have almost horizontal movement of water particles. Therefore, different types of wave energy converters are designed for different depths of the sea.

Offshore devices, like buoys, are able to utilize the vertical force component of the waves. Near-shore devices, like bottom-hinged flaps, utilize the horizontal wave forces. One solution able to utilize both horizontal and vertical force components could be a horizontally aligned cylinder moving elliptically during the wave. In addition, the possibilities of non-symmetrical devices like Salter's Duck are theoretically shown [3].

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Nomenclature

a	Radius m
d	Water depth m
$\dot{E}_S$	Mean energy flux of the wave energy converter W/m
$\dot{E}_W$	Mean energy flux per wave W/m
F_H	Horizontal wave force component on the cylinder N
F_{spring}	Force of the spring N
F_V	Vertical wave force component on the cylinder N
g	Acceleration of gravity m/s^2
h	Depth of the cylinder m
H	Wave height m
L	Wavelength m
p	Pressure Pa
P_S	Wave power on the cylinder W
r	Polar radial coordinate m
t	Time s
T	Wave period s
u	Horizontal velocity component of fluid m/s
u_r, u_θ	Velocity components in polar coordinates m/s
u_{wave}	Horizontal velocity component of a water particle m/s
U	Horizontal velocity component of an oscillating cylinder m/s
U_0	Maximum horizontal velocity of an oscillating cylinder m/s
v	Vertical velocity component of fluid m/s
v_{wave}	Vertical velocity component of a water particle m/s
V	Vertical velocity component of an oscillating cylinder m/s
V_0	Maximum vertical velocity of an oscillating cylinder m/s
x	Cartesian coordinate m
y	Cartesian coordinate m
η	Efficiency of the wave energy converter -
θ	Polar coordinate rad
ρ	Density kg/m^3
Φ	Velocity potential m^2/s
Φ_f	Velocity potential of the fluid flow around a not moving cylinder m^2/s
Φ_c	Velocity potential around a cylinder moving in ideal fluid m^2/s
Φ_{fc}	Velocity potential around a cylinder moving in fluid flow m^2/s
Φ_{wave}	Velocity potential of a wave m^2/s
Ψ	Stream function m^2/s
φ	Phase shift rad

Transportation of the end products, electricity and, in the case of wave-powered desalination, fresh water, is expensive far from the shore. A short distance between the harbor and the device enables even small weather windows for installation and maintenance. These cost reductions may be significant since operation and maintenance costs can be about 40% of the net present cost of a wave energy converter. Shallow water also filters out the largest waves reducing the maximum loads required for survival; the placement in the breaking wave zone may negate this advantage [4]. Some coasts, however, deepen very fast and are well-suited for wave energy utilization.

To define the exact interaction between the waves and the converter is a complex task and there are no simple models for calculating the actual process. The issue has been approached before using linear hydrodynamic numerical models among others for flap configurations [5]. A comparison between different wave energy devices was committed in [6] where the power matrices of one floating oscillating water column and seven oscillating bodies were determined by using numerical models. The leading and widely studied wave energy technologies are the oscillating water column and the point absorber; the interaction between waves and buoys is numerically approached e.g. in [7].

In this study, we take a different approach and perform an analytical model using a cylindrical wave energy converter. There are earlier calculations of wave forces on marine structures [8,9] and especially on fixed vertical piles. This thought is utilized here; the most significant difference is the horizontally aligned cylinder, shown in Fig. 1, oscillating in two modes. The cylindrical converter pressurizes water with four hydraulic cylinders. The product of the process, either fresh water or electricity, is transferred to the beach via cables. The whole system is installed on the bottom of the sea. Letting the converter oscillate in both horizontal and vertical directions enables higher power capture from the waves and improves the efficiency of the converter. Theoretically can be shown that symmetrical wave energy converters oscillating in one mode of motion are capable of only 50% energy absorption and symmetrical converters utilizing two modes of motion as well as non-symmetrical converters are able to absorb all incident wave energy [10].

2. System description

The energy converter studied in this work is a horizontally orientated cylinder which may be placed at different depths in the sea. The cylinder can oscillate in horizontal and vertical directions and transfer mechanical energy forward by hydraulic cylinders situated at both ends of the converter. The effect of the buoyancy is compensated by a spring fixed to the cylinder. Operation of the wave energy converter in waves is shown in Fig. 2. The dimensions of the system are also included in the figure: H is the wave height, L the wavelength, d the water depth, a the radius of the cylinder and h the distance between the center of the cylinder and still water level. The horizontal velocity of the cylinder is $U(t)$ and the vertical velocity is $V(t)$.

The purpose of the study is to find with the aid of potential flow theory and with Euler's equations the pressure distribution $p(r=a,\theta,t)$ along the surface of the cylinder and, on the basis of this, calculate the horizontal and vertical forces $F_H(t)$ and $F_V(t)$, respectively, affecting the cylinder. In reality, also the viscous forces on the surface are quite important, but to simplify the model they are ignored here. Viscous forces imply dissipation effect which lowers the efficiency to some extent. The power transferred from the waves to the cylinder is then $P_S(t) = [\overline{F}(t) + \overline{F}_{spring}(t)] \cdot \overline{v}(t) = F_H(t)U(t) + F_V(t)V(t) + \overline{F}_{spring}(t) \cdot \overline{v}(t)$ where the instantaneous velocity of the cylinder is $\overline{v}(t) = (U(t), V(t))$. Even though the force of the spring affects the instantaneous power, it has no effect on the mean energy flux of the converter: $\dot{E}_S = \frac{1}{T}\int_0^T P_S \mathrm{d}t = \frac{1}{T} = \int_0^T [F_H(t)U(t) + F_V(t)V(t)]\mathrm{d}t + \frac{1}{T}\underbrace{\int_0^T \overline{F}_{spring}(t) \cdot \overline{v}(t)\mathrm{d}t}_{=0}$.

3. Interaction between waves and oscillating wave energy converters

3.1. Potential flow

To study the interaction between the waves and the wave energy converter, we will use potential flow theory separately both