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Flow and performance characteristics of a direct drive turbine for wave power generation

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ABSTRACT

A cross-flow turbine, also known as Banki turbine, is a hydraulic turbine that may be classified as an impulse turbine. It has gained interest in small and low head establishments because of its simple structure, cost effectiveness and low maintenance. The present work expands on this idea and aims to implement a cross-flow turbine as Direct Drive Turbine (DDT) for wave power generation. Waves have enormous amount of energy which is environment-friendly, renewable and can be exploited to satisfy the energy needs. A Numerical Wave-tank (NWT) was used to simulate the waves using the commercial CFD code ANSYS-CFX. The base model was firstly studied at five different wave periods without the turbine. The highest water power (PWP) of 32.01 W was recorded at $T=3$ s. A cross-flow turbine was then incorporated and the simulation was validated at $T=2$ s. In addition to this, the performance of the turbine at $T=2.5$ s and $T=3$ s at different turbine speeds was also studied. The highest turbine output power of 14 W was recorded at a turbine speed of 30 rpm at the wave period of 3 s, giving a turbine efficiency of 55%.

1. Introduction

Power generation utilizing renewable sources has become a common practice recently, reflecting the major threats of climates change due to pollution, exhaustion of fossil fuels, and the environmental, social and political risks of fossil fuels. Fortunately, renewable energy sources are available in many countries and this can be exploited to satisfy energy needs with little or no impact on the environment. Hydro-power has always been an important energy resource and wind power has its share of success. However, there exists another source which contains vast amount of energy – the ocean energy. Ocean contains energy in the forms of thermal energy and mechanical energy: thermal energy from solar radiation and mechanical energy from the waves and tides. The generation of power with ocean waves is presented in this paper.

Ocean waves arise from the transfer of energy from the sun to wind and then water. Solar energy creates wind which blows over the ocean, converting wind energy to wave energy. This wave energy can travel thousands of miles with little energy loss. Most importantly, waves are a regular source of power with an intensity that can be accurately predicted several days before their arrival (NOAA Central Library, 2011). Wave is available 90% of the time compared to wind and solar resources which are available 30% of the time. In addition to this, wave energy provides somewhat 15–20 times more energy per square meter than wind or solar (Wavemill Energy Corp., 2011). There is approximately 8000–80,000 TWh/year or 1–10 TW of wave energy in the entire ocean, and on average, each wave crest transmits 20–50 kW/m.

Wave power refers to the energy of ocean surface waves and the capture of that energy to do useful work. There are many energy devices or energy converters available that can be used to extract power from ocean surface waves. The interest in wave energy extraction started way back and a number of devices were proposed and studied by Isaacs et al. (1976), McCormick (2007), Falnes and Budal (1978), Falnes (2002) and Stahl (1892). Japanese wave-power pioneer Masuda (1985), Salter (1974, 1989), Budal and Falnes (1977) and McCormick (1974) were leading pioneers and have made significant contribution to the field of wave energy conversion. Wave energy conversion devices have stimulated the imagination of designers such as Drew et al., 2009; Falnes, 2007; Thorpe, 2000; Bedard, 2007a; Bedard et al., 2010; Meisen and Loiseau, 2009 and given birth to a lot of new concepts. Wave power devices are generally categorized by the method used to capture the energy of the waves. They can also be categorized by the location and power take-off system. Few of the best known

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Nomenclature

A	amplitude (m)
A_{CS}	cross sectional area (m^2)
C_f	first stage energy conversion factor (–)
c_g	group velocity (m/s)
c_p	phase velocity (m/s)
d	water depth (m)
E	energy density (J/m^2)
g	acceleration due to gravity (m^2/s)
H	wave height (m)
H_{0i}	cross sectional height at section I (m)
ΔH	head difference (m)
P_{Avail}	available power at front guide nozzle inlet (W)
P_T	turbine power (W)
P_{WP}	water power (W)
P_{Wave}	wave energy flux (W/m)
Q	volume flow rate (m^3/s)
t	timestep (s)
T	wave period (s)
T_{ave}	average turbine torque (N $\cdot$ m)
V	volume (m^3)
W_G	front guide nozzle inlet width (m)
W_{0i}	cross sectional width at section I (m)
x_{dis}	wave maker displacement (m)
ΔY	rear chamber water level difference (m)
α	front guide nozzle divergence angle (°)
η_T	turbine efficiency (–)
λ	wavelength (m)
ρ	water density (kg/m^3)
ω	angular velocity (rad/s)
ω_0	frequency (Hz)

device concepts are point absorbers, overtopping terminators, attenuator and Oscillating Water Columns (OWC).

Point absorber utilizes wave energy from all directions at a single point by using the vertical motion of waves (Bedard, 2007b). The length (along the direction of wave propagation) and width of a point absorber are small compared to the usual wave length. The majority of wave energy converter designs are point absorbers for instance the AquaBuoy by Finavera Renewables Inc. (Global Greenhouse Warming.Com, 2011). Wave energy devices oriented perpendicular to the direction of the wave are known as terminators. In overtopping terminators, the wave is first concentrated by wings and then focused towards a central reservoir. The amplified waves surge up a ramp and fill a reservoir at a level above sea level. The potential energy of the water trapped in the reservoir is then converted to electrical energy through a low head turbine which is connected to a generator. Perhaps the best known overtopping device today is the Wave Dragon (Wave Dragon, 2011). Attenuator, sometimes called linear absorbers are long multi-segment floating structures oriented parallel to the direction of the waves. The differing heights of waves along the length of the device causes flexing where the segments connect, and this flexing is connected to hydraulic pumps or other converters (Union of Concerned Scientists, 2011) for instance the Pelamis (Pelamis Wave Power, 2011). Another such device is the Irish McCabe Wave Pump (U.S. Department of Interior, 2006).

Oscillating Water Column (OWC) – is a partially submerged, hollow structure positioned, either vertically or at an angle, normally in shallow water or onshore. OWC uses the same principle as a piston in an engine. It generates electricity in a two-step process. As a wave enters the column, there is an increase in the pressure of entrained air which is held over the column of water; this air is then forced past a turbine. As the wave retreats, the air is drawn back past the same turbine due to the reduced air pressure on the ocean side of the turbine. Most commonly, a Wells turbine is used in OWC because it has the advantage of rotating in the direction irrespective of the airflow direction. However, Savonius rotors are also proposed and tested for OWCs (Ram et al., 2010). Onshore OWC is relatively cheap because there is no need for sub-sea grid connection, easier to maintain and has easy accessibility. However, onshore OWC devices capture less wave energy due to the loss of energy to seabed friction when compared to its near-shore and offshore counterparts.

Literature review shows there are varieties of wave energy devices in existence which can be employed to extract power form ocean surface waves. There is a vast amount of knowledge and it can be further used to develop new devices or even improve on the existing devices. Oscillating Water Column (OWC) is one of the best designed concepts to extract wave energy. However, all the existing OWC use air turbines to convert the pneumatic energy (compressed air) to mechanical and then electrical energy. The turbines that use the oscillating flow of air have problems such as relatively high rotational speed variation and aerodynamic losses due to high noise coming from the turbine passage at extreme sea conditions. To address this problem, Fukutomi and Nakase (1990) and Choi et al. (2007, 2008) have proposed a Direct Drive Turbine (DDT) which uses water as the working fluid. Prasad et al. (2010) presented the results from a detailed study of the effect of front guide nozzle shape on energy conversion in DDT for wave power generation. The turbine is fully submerged in water and under the action of incoming waves generates power bi-directionally. Therefore, the present study aims to use a DDT of the cross-flow type (Banki Turbine) to generate power from ocean surface waves. The cross-flow turbine is widely used for hydro-power applications and it possesses many advantages; as stated by Olgun (1998), apart from cost-effectiveness and ease of construction; it is self-cleaning, there is no problem of cavitation and its efficiency does not depend much on the flow rate compared to other types of turbines.

A Numerical Wave-tank (NWT) is used in the present work and the waves in the numerical wave-tank were generated by a piston type wave maker which was located at the wave-tank inlet. The paper is divided into two parts. The first part looks at the flow characteristics and primary energy conversion in the base model at different wave periods without the turbine. More specifically, the flow in the front guide nozzle and the augmentation channel is studied. The second part involves simulation including the cross-flow turbine. The model was first validated with experimental data at a wave period of 2 s. Upon this, the model was further tested at wave periods of 2.5 s and 3 s at different turbine speeds. The entire model is solved in a commercial CFD code ANSYS-CFX.

2. Methodology

2.1. Experimental setup

To test the accuracy of numerical method used to generate waves in NWT the code was validated against experimental data. The experiments were conducted in a 2D wave channel having a length of 35 m, width of 1 m and depth of 1 m as shown in Fig. 1. The turbine test section was located 15 m downstream of the