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Mechanical design and modeling of a single-piston pump for the novel power take-off system of a wave energy converter

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ABSTRACT

A multi-pump, multi-piston power take-off wave energy converter (MP^{2}PTO WEC) has been proposed for use with a novel renewable energy harvester termed the Ocean Grazer. The MP^{2}PTO WEC utilizes wave motion to pump—via buoys connected to pistons—working fluid within a closed circuit and store it as potential energy that can be converted to electricity via turbines. This paper introduces the mechanical design and model-based performance prediction of a single-piston pump that constitutes the basic building block for the MP^{2}PTO WEC. Results provide preliminary validation of aqueous lubrication as a viable means of reducing friction and wear, suggesting that water-based hydraulic fluids can prohibit solid contact at the piston-cylinder interface while reducing volumetric leakage, and allowing for an estimation of the energy extraction efficiency for the mechanical pumping system. Pending more thorough and extended tribological investigations using the methodology introduced in this paper, findings suggest that the overall system efficiency will be dictated by the hydrodynamics of the buoys actuating the pumping system.

1. Introduction

A number of near- and off-shore wave energy converters (WECs) have been proposed in recent years based on attenuator [1,2], point absorber [3], overtopping [4], and other design principles; for a comprehensive review of existing WEC technologies, the reader is referred to a recent report published by the Strategic Initiative for Ocean Energy [5]. In an effort to improve on the state-of-the-art, the University of Groningen has patented a novel semi-submersible renewable energy harvester, termed the *Ocean Grazer*, with a *multi-pump, multi-piston power take-off (MP^{2}PTO)* WEC at its core. A single Ocean Grazer device, for which the MP^{2}PTO WEC employing multiple multi-piston pump units will contribute about 80% of power generation (secondary technologies such as oscillating water column and wind turbine systems will contribute the rest), is projected to produce more than 200 GWh/year and have a storage capacity of about 800 MWh [6,7].

The operating principle of the MP^{2}PTO WEC, shown in Fig. 1(a), is to create pressure difference (hydraulic head, H) in the working fluid circulating between two reservoirs that can be transformed into electricity via a turbine (T). A modified point absorber design will be used such that floating buoys (B_i) will follow the motion of an incident wave and actuate linear hydraulic pumps (P_i) to move the working fluid column during the upstroke. In this manner, the working fluid can be pumped to the upper reservoir where it will be stored as lossless potential energy, and allowing for the decoupling of electricity generation from the variability of available wave energy over timescales of seconds (for individual waves) to hours and days.

Varying sea conditions determine an incident wave's characteristics such that each wave may differ significantly from those preceding or following it; ideally, a WEC should be able to extract energy from both small and large waves with a range of periods. Energy extraction is expected to diminish the energy content and height of a wave as it moves through a WEC. In the case of the Ocean Grazer, which will employ a grid of buoys – termed a *floater blanket* – to actuate the pumps, the first pump unit can potentially extract more energy than the second, and so on. To account for the inherent variability in wave energy content, multiple pistons will

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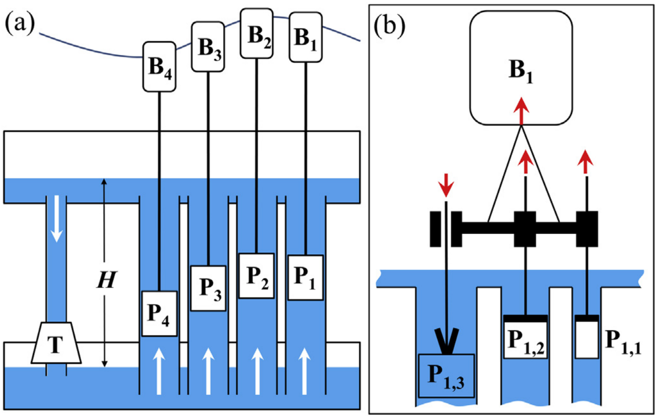

Fig. 1. The MP^{2}PTO WEC (a) and multi-piston pump (b).

be activated within each pump in the Ocean Grazer, as shown in Fig. 1(b), to maximize energy extraction for waves ranging in height from 1 to 12 m and periods of 4 to 20 s [6,7]: controlling the coupling between any buoy (B_i) and a number of variable-size pistons ($P_{i,j}$) can optimize the load the buoy has to carry to achieve resonance during the upstroke and let an uncoupled piston sink due to its own weight during the downstroke. Preliminary work has demonstrated the successful potential use of variable-load control for a multi-piston pump [8]; however, the focus of the present work is the tribological characterization of the behavior of a single-piston pump unit – that will constitute the basic building block for the multi-piston and, eventually, the MP^{2}PTO WEC – in order to better understand the dynamic behavior of the piston based on physics-based formulations of the forces and pressures acting on it. While variable-load control is not discussed within the context of the present model, this work will be essential in the future design and implementation of improved control schemes [9]. Similarly, previously developed methodologies for a hydro-pumped storage system utilizing a number of pumps in parallel operation will be useful in the eventual transition from a single-to a multi-pump system [10,11].

The main tribological interfaces of interest in the MP^{2}PTO WEC are between the piston and cylinder and at the seals that isolate the working fluid from sea water while allowing for the cable connections to transfer the buoy motion to the pistons. While the sealing problem is important because of sea water's highly corrosive and biofouling attributes, it is not addressed in the current work. Instead, it is assumed that perfect sealing is achieved so that the working fluid circulation is completely isolated from sea water, while buoy motion is transferred without frictional losses to the piston via a cable or rod of known stiffness. Future research on the tribology of the cable-seal interface will allow for the relaxation of these assumptions, especially within the context of flexible diamond-like carbon coatings that can be used in rubber seals [12]. Flexible coatings will also be relevant in secondary tribological interfaces between the piston and piston flaps as well as the one-way valves preventing working fluid backflow.

Scaling and maintenance issues require the design and use of a robust and abundant lubricant supply to the tribological interfaces. This suggests that a water-based hydraulic fluid optimized for the operating conditions of the piston-cylinder interface could potentially be used as a lubricant. Aqueous lubrication [13] was initially investigated within the context of environmental humidity at tribological interfaces [14], and subsequently for use with polymer composite coatings [15–17], and ceramic coatings with [18] and without texturing [19]. As a starting point, the present work assumes that a water-based hydraulic fluid (e.g. ISO Class HFC, a watery polymer solution) is used as the working fluid, while thermal effects are neglected at the piston-cylinder interface, where elastohydrodynamic (EHL) lubrication regimes are expected. Similarly to reciprocating engines [20], Sterling engines [21] and ring-less compressors [22], piston motion could result in boundary lubrication when the relative velocity at the interface becomes close to zero (at the top- and bottom-dead-centers), while EHL can be maintained otherwise. One of the questions to be answered with this work is whether EHL can be maintained throughout the piston stroke. Focusing on the piston-cylinder interface, the present model adopts existing methodologies to analyze the incompressible, inviscid and isothermal EHL problem. Future work will investigate the potential inclusion of piston rings, which may reduce working fluid backflow but increase friction, thereby complicating the lubrication issue.

A two-degree-of-freedom (2DOF) dynamical model comprising switching-state (upward versus downward motion), second order equations with an external forcing function was formulated in previous work [7,8]. This did not include friction and simplified the lubrication regime at the piston-cylinder interface by assuming hydrodynamic (Couette) flow. The current model builds on this dynamical model by adding EHL and solid contact and friction forces at the piston-cylinder interface based on solutions of the EHL problem. Further improvements to the model are planned in future work, including the formulation of realistic (irregular) wave displacement profiles serving as the external excitation, and accounting for the loss of wave energy content (and height) in the downstream direction due to energy extraction relevant for the MP^{2}PTO WEC; the inclusion of additional degrees of freedom for the piston and the buoy, such as downstream translation depending on buoy hydrodynamics; and, the improved modeling of dynamical piston behavior including piston flap (valve) dynamics and the drag force acting on the piston during sinking within the fluid column as a function of piston design.

The overall efficiency of the Ocean Grazer will depend on frictional and hydrodynamic energy losses at the MP^{2}PTO WEC. Therefore, minimizing friction and understanding the hydrodynamic behavior of grids of buoys are of paramount importance to maximize wave energy extraction as is reducing wear to ensure robust operation with little need for maintenance, especially in the presence of multiple tribological interfaces. Our results show that volumetric leakage at the piston-cylinder separation is critical in determining the overall pumping efficiency: this will decrease to below 80% for piston-cylinder separations larger than 200 μm, a finding that agrees with computational fluid dynamics simulations [23], pointing to target piston-cylinder separations around 100 μm when pure water is used as a lubricant. Such separations are comparable to those used in relevant applications such as ringless compressors, diesel and Sterling engines with typical values of 10 μm, 63 μm and 500 μm, respectively, and their optimization will be the focus of future work [20–22]. The present model is the first step in validating the pumping system's mechanical efficiency that has been measured in a small-scale prototype to be close to 99% and, hence, the potential of the Ocean Grazer to becoming a viable renewable energy harvester.

2. Dynamical model formulation

2.1. Piston excitation due to wave motion

The issue of wave hydrodynamics and their effects on floating structures is not trivial and has received significant attention in the literature [24,25], especially with reference to the control of point absorber WECs [26,27]. The scattering of an incident wave induces