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A performance study of a horizontal-axis micro-turbine in a numerical wave flume

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Abstract

Numerical studies of performance of a 3-bladed Savonius type horizontal-axis wave energy converter are presented. Numerical simulations based on a volume of fluid (VOF) method coupled with a finite volume method (FVM) approach are performed in a numerical wave flume (NWF) for specified values of flow physics and turbine blade geometry conditions. Once validated against experimental data, the numerical simulations are extended to investigate the overall performance of the turbine over a very large range of wave height, wave frequency, and the submergence level for the same water depth in the context of optimization of a design of a small scale Savonius rotor. From the numerical results obtained and validated against the experimental data it can be concluded that the flow characteristics are strongly dependent upon differing wave propagation conditions and energy conversion rate can be increased with a proper combination of selected wave height and frequency for the investigated parametric value range.

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1. Introduction

Fundamental wave energy conversion devices are mainly classified in three groups depending on how they interact with the ocean waves. In the first group, the turbine-type oscillating water columns (OWC) are devices that

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involve creating a structure on the shoreline such that waves enter and leave a static chamber. In the second group, overtopping devices consist of a structure which collects incoming waves by creating a reservoir into which only high waves may crash. In the third group, surface devices which directly use the motion of the ocean surface. They generally include a floating surface that moves up and down due to the buoyancy force of waves.

There have been number of experimental and numerical studies conducted for energy conversion analysis and performance research on ocean wave- energy converter (OWEC) devices constructed and tested in form of scale models in an experimental wave flume [1-6] and/or numerical wave flume [7-9]. These studies mainly focus on parametric analysis of design of such devices for increase of their wave energy conversion efficiency for a range of wave height, length and period and physical/geometrical constraints in relation to the wave motion. Modern wave channel instrumentations with the imposition of wave making technologies, PIV measurement and computer vision techniques to study of water waves can provide an ideal working medium for different types of scale models of OWEC devices in experimental wave flumes [2-4].

The aim of the present study is to numerically explore the non-linear, two-dimensional, viscous, unsteady and turbulent wave flow behavior over a Savonius rotor in comparison with the present authors´ previous experimental study [5] to provide possible solutions/suggestions for increasing hydrodynamic energy conversion efficiency of such devices by considering different operating conditions. The numerical analysis of Savonius rotor performance at intermediate-to-shallow water depths is not available in the known literature, and this is also motivation for the present study.

2. Mathematical principles

2.1. Governing equations

The basic flow equations governing the present turbulent flow behavior around a rotating constructed Savonius rotor structure are continuity and momentum conservation equations, i.e. Reynolds averaged Navier-Stokes (RANS) equations and transport equations for turbulence quantities. These conservation equations written in non-linear differential form of tensor notation for incompressible, viscous fluid flow conditions can be summarized below. For the present study, a fixed orthogonal coordinate system with origin at the center of the rolling cylinder is used for differential form of these equations.

$$\frac{\partial \bar{u}_i}{\partial x_i}=0 \tag{1}$$

$$\rho\frac{\partial \bar{u}_i}{\partial t}+\rho\bar{u}_j\frac{\partial \bar{u}_i}{\partial x_j}=-\frac{\partial \bar{P}}{\partial x_i}+\frac{\partial}{\partial x_j}\left(\mu\frac{\partial \bar{u}_i}{\partial x_j}-\rho\overline{u'_i u'_j}\right)+\rho g_i \tag{2}$$

where ρ is the fluid density, $\bar{u}_i$ is the time averaged velocity, x_i is the coordinate direction, u'_i is the deviation from the time averaged velocity, $\bar{P}$ is the time averaged pressure, g is gravity acceleration, μ is the dynamic viscosity of the fluid, $-\rho u'_i u'_j$ is the Reynold's stress tensor which appears on the right hand side of the RANS equations as a result of time averaging to the Navier-Stokes equations. The temporal and spatial co-ordinates correspond to t and x_i, respectively.

In eddy viscosity based k-ε turbulence models the turbulence field is characterized in terms of two transport variables, kinetic energy and its dissipation rate related to the time averaging to enclose the RANS equation (2) above. In the present study, the proposed model is based on Re-Normalised Group theory and is referred to as the RNG k-ε turbulence model [10]. This model is similar in form to the standard turbulence model; however the RNG turbulence model differs from the standard model by the inclusion of an additional sink term in the turbulence dissipation equation to account for non-equilibrium strain rates and employs different values for the various model coefficients.

In the present study, the volume of fluid element (VOF) method, initially proposed by Hirt and Nichols [11] is used as an algebraic volume-tracking method, in which air-water interface is not tracked explicitly but implicitly