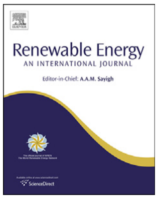
Renewable Energy 80 (2015) 275–285

Contents lists available at ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene



Effect of hydrofoil flexibility on the power extraction of a flapping tidal generator via two- and three-dimensional flow simulations

Tuyen Quang Le [b], Jin Hwan Ko [a, *]

[a] Korea Institute of Ocean Science & Technology, Ansan 426-444, Republic of Korea
[b] Institute of High Performance Computing, Singapore 138632, Singapore

ARTICLE INFO

Article history:
Received 10 February 2014
Accepted 30 January 2015
Available online

Keywords:
Flapping tidal generator
Chordwise flexure
Spanwise flexure
Power-extraction efficiency
Three-dimensional effect

ABSTRACT

In this study, we investigate the effect of hydrofoil flexibility on the power extraction of a flapping tidal stream generator with hydrofoils down-scaled for a water channel in an experiment with a typical Strouhal number and frequency. The described deformations in the chord and spanwise directions are imposed onto the surfaces of the hydrofoil to analyze the flexibility effect. In a two-dimensional (2D) simulation, parameter studies of the chordwise flexure are conducted and a 30% improvement in the rate of the power-extraction efficiency is then achieved when the chordwise flexure is 20% of the chord length. In a three-dimensional (3D) simulation, the chordwise flexure of 20% achieves a 15% improvement in the rate of the power-extraction efficiency for the hydrofoil with an aspect ratio (AR) of 5, which is less than that in the 2D simulation due to 3D effects such as tip loss and a spanwise vortex. Meanwhile, the effect of the spanwise flexure on the power extraction is minor as compared to that of the chordwise flexure. It was also found throughout the parametric study of the AR variation that the 3D effect of the chordwise flexible hydrofoil is slightly stronger than that of the rigid hydrofoil.

1. Introduction

Tidal stream energy has been considered as one of renewable energy sources in order to reduce our dependency on fossil fuels. So far, most tidal stream generators have been developed in three types: horizontal axis, vertical axis, and flapping type generators [1]. Among them, the flapping type devices are still in a nascent status as compared to the rotary-type turbines with horizontal and vertical rotational axes [2–5]. In 21 century, the several flapping systems as commercial products have been designed, developed or installed. Meanwhile, the flapping systems still need improvement in power-generating capability, controllability and structural safety in order to be considered as a viable alternative of the rotary-type generators despite the fact that they are known to be eco-friendly systems due to relatively low tip speed [6].

The flapping generators have been investigated in both experimental and numerical studies in recent years. As a first attempt, in the 1980s, an experimental study showed that wind energy could be extracted from a flapping foil while coupling the pitch and plunge motions in the proper conditions [7]. Later, the optimal efficiency of a flapping generator was determined through parameter studies. An experimental study with an aluminum NACA0012 hydrofoil explored power-extraction efficiency as the function of the Strouhal number, the phase angle between the pitch and plunge motion, and the angle of attack. A maximum efficiency of 43% was achieved under an optimal condition in which Strouhal number was 0.4 and the maximum angle of attack was 34.4° with a phase angle difference of 90° between the pitch and plunge motions [8]. The pitching axis location within chord lengths of 0.2–0.5 from the leading edge was recommended based on a study considering constrained sinusoidal pitching motion [9]. When the pitching axis was close to the downstream area of the mid-chord point, self-induced oscillation was presented in experimental studies, particularly those of Semler [10]. For a dual-foil configuration, the results from a two-dimensional simulation showed good agreement with the experimental results of a 2 kW prototype, and the three-

---

* Corresponding author.
E-mail address: jhko@kiost.ac (J.H. Ko).

http://dx.doi.org/10.1016/j.renene.2015.01.068
0960-1481/

dimensional effect on a flapping tidal generator was also investigated by Kinsey and Dumas [11,12]. In that study, the drop in the hydrodynamic performance due to the finite span length was determined as compared to a two-dimensional case. According to the results, the endplate at the foil tip and the high aspect ratio foil were proposed to minimize the tip loss; with them, the reduction in the performance of the three-dimensional foil could be limited to around 10% as compared to the two-dimensional foil.

Thus far, wing flexibility mimicked from flapping flying or swimming creatures is well known as a key factor to improve the level of propulsive efficiency. Experimental studies on the propulsive systems were intensively conducted, hence optimal efficiency, correlation between leading edge vortex (LEV) and spanwise flow were figured out [13–15]. When the Strouhal number is larger than 0.2, moderate spanwise flexibility can induce a slight increase in the thrust and a slight decrease in the required power, yielding high propulsive efficiency in a water channel experiment [16]. A stronger LEV in a flexible wing was observed in these experiments as compared to that in a rigid wing. A two-dimensional numerical simulation with a fluid–structure interaction model showed that a flexible ray with leading edge strengthening could improve the thrust and propulsive efficiency [15]. In contrast to propulsive systems in which thrust is required, the flapping tidal generator creates a high drag while its power is mainly extracted from lift. Therefore, chordwise and spanwise flexibility can be utilized to improve the power-extraction efficiency of a flapping tidal generator by alternating the size of the LEV and by synchronizing the phase of the instantaneous lift force and plunge velocity. Recently, a two-dimensional numerical simulation of a flapping hydrofoil with local described deformation was carried out to investigate the benefits of flexibility on the extraction of power [17]. The results showed that a flexible hydrofoil is beneficial to enhance the power-extraction efficiency by increasing the peak of the lift and shifting the phase between the instantaneous lift force and plunge velocity in a favorable pattern.

In this study, the effects of chordwise as well as spanwise flexure on the power-extraction efficiency of a flapping hydrofoil are investigated through two-dimensional and three-dimensional numerical simulations with an in-house code. The dimensions of the flapping hydrofoil and the operating condition were determined by considering the water channel in lab-scale experiments. The amounts of chordwise and spanwise deformations were directly determined by quadratic functions in the simulations. In addition, the effects of the aspect ratio of the hydrofoil on the power-extraction efficiency were explored.

2. Numerical method

2.1. Flow solver

The power extraction performance of a flapping hydrofoil is estimated by an in-house parallelized multi-block structured Navies–Stokes solver, which is named as KFLOW [18,19]. The time-dependent viscous flow around the flapping foil is simulated by solving the preconditioned Reynold-Averaged Navies–Stokes equation as below

$$\Gamma^{-1}\frac{\partial W_T}{\partial \tau}+\frac{\partial W}{\partial t}+\frac{\partial (F_i+F_{vi})}{\partial x_i}=0 \quad (i=1,2,3), \tag{1}$$

where Γ^{-1} is the time-derivative preconditioning matrix, τ is the pseudo time, t is the real time, W_T is the primitive flow variable, and W is the conservative flow variable; F_i and F_{vi} are the inviscid and viscous fluxes in each direction, respectively. W_T, W, F_i and F_{vi} are defined as follows:

$$W_T=\begin{bmatrix} p \\ u_i \\ T \end{bmatrix}, \quad W=\begin{bmatrix} \rho \\ \rho u_i \\ \rho E \end{bmatrix}, \quad F_i=\begin{bmatrix} \rho u_i \\ \rho u_i u_j + p\delta_{ij} \\ \rho u_i H \end{bmatrix},$$
$$F_{vi}=\begin{bmatrix} 0 \\ \tau_{ij}+\tau^*_{ij} \\ u_i\left(\tau_{ij}+\tau^*_{ij}\right)-q_j+(\mu_l+\sigma_k\mu_t)\dfrac{\partial k}{\partial x_i} \end{bmatrix}. \tag{2}$$

Here, the pressure p and the temperature T are expressed in perturbed forms to decrease the round-off and the cancellation errors in very low Mach number flows. ρ is the density and u_i is the velocity component. E is the total energy and H is the total enthalpy. The quantity τ_{ij} and $\tau^*{}_{ij}$ are the laminar and turbulent stresses, respectively, and q_i is the heat flux in each direction. Γ^{-1} is used to contain the compressible effect and to reduce the stiffness problem in low Mach number flows by scaling the acoustic wave speeds with a preconditioned velocity scale [20]. The governing equation was used in the numerical simulations for flexible flapping wing propulsion as well [21].

The accuracy of KFLOW in studying a flapping foil was validated in previous works [22–25]. Inviscid, laminar and several turbulent models are available in KFLOW. In the following simulations of the flapping tidal generators, a turbulent scheme, k-ω is used; it has been selected to simulate turbulent flow in energy extraction from flapping foils [12,17,26]. For the spatial discretization, the Roe flux difference slitting scheme and the third-order MUSCL are used with Van Albada limiter to obtain the secondary accuracy of inviscid flux. The central difference is used to calculate the variable gradient of viscous flux. The dual-time stepping with the diagonalized alternate directional implicit (DADI) method is used to advance the solution in time. This allows not only the use of a large time increment but also the maintenance of temporal accuracy. Moreover, the dual-time stepping also eliminates factorization and linearization errors by iterating the solutions along a pseudo-time, and the detail description is provided in Ref. [27].

The Chimera mesh option is used due to its advantage in handling the relative motion between meshes [28]. In this Chimera overset method, a cut-paste algorithm is applied to compose a cross section that exchanges information between grids, which enables the generation of overlapping grids with moderate mesh interface regions. The overlapped grid method combines two major steps: hole cutting and donor identification [29]. Specially for flapping tidal power extraction, a large pitch angle is mandatory; hence, the Chimera mesh is essential. Fig. 1 shows the body-fitted and domain meshes used in the simulations. The Chimera mesh is composed of a C-type mesh around a hydrofoil as the body-fitted mesh and an H-type mesh for the rest of the computational domain as the domain mesh in two-dimensional (2D) and three-dimensional (3D) simulations. In the 2D simulation, the distance from the foil (the body) to the far-field and inlet boundaries is set to 20 times of the chord length (20c), while the distance from the foil to the outlet boundary is elongated to 25c; thus, domain size becomes 40c × 45c. Specially, in order to resolve vorticity shedding well, a fine mesh is created in the downstream zone, as shown in Fig. 1A. In this study, the power extraction of the flapping foil directly depends on force and moment on the foil, therefore high quality grid that obeys the criterion of orthogonality and stretching near the foil is used as shown in Fig. 1B. Similarly, the domain sizes of the 3D simulation are 25, 20 and 20 times of the chord length in length, height and width directions, as shown in Fig. 1C. The closed view of the mesh in vicinity of the 3D foil is depicted in Fig. 1D. The numerical convergence by the grid density variation will be presented in Section 3.1.