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Performance analysis of a HAT tidal current turbine and wake flow characteristics

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ABSTRACT

Having very strong current on the west coast with up to 10 m tidal range, there are many suitable sites for the application of tidal current power (TCP) in Korea. The turbine, which initially converts the tidal energy, is an important component because it affects the efficiency of the entire system. To design a turbine that can extract the maximum power on the site, the depth and duration of current velocity with respect to direction should be considered. To extract a significant quantity of power, a tidal current farm with a multi-arrangement is necessary in the ocean. The interactions between devices contribute significantly to the total power capacity. Thus, the study of wake propagation is necessary to understand the evolution of the wake behind a turbine. This paper introduces configuration design of horizontal axis tidal current turbine based on the blade element theory, and evaluating its performance with CFD. The maximum efficiency of the designed turbine was calculated as 40% at a tip speed ratio (TSR) of 5. The target capacity of 300 kW was generated at the design velocity, and the performance was stable over a wide range of rotating speeds. To investigate the wakes behind the turbine, unsteady simulation was carried out. The wake velocity distribution was obtained, and velocity deficit was calculated. A large and rapid recovery was observed from 2D to 8D downstream, followed by a much slower recovery beyond. The velocity was recovered up to 86% at 18D downstream.

1. Introduction

Ocean energy, including tidal current power (TCP) among numerous alternative energy sources, has the greatest potential for use throughout the world. The kinetic energy available within a tidal current can be converted into rotational power by a turbine; therefore, turbine design and performance verification is important in developing TCP systems. Many studies have been performed on tidal turbine design based on the blade element momentum theory (Batten et al. [1], Baltazar and de Campos [2]). Bahaj et al. [3] conducted an experimental demonstration of tidal turbine performance. Jo et al. [4] compared the performance of three different types of turbines by experiment. Jo et al. [5] investigated the interference effects of multi-arrayed turbines. Faudot and Dahlhaug [6] introduced a performance analysis for tidal turbines under the effects of regular waves.

In this study, a horizontal axis turbine (HAT) was designed based on the blade element theory and validated using computational fluid dynamics (CFD). Performance of the turbine was verified by experiment in a circulating water channel (CWC) and compared with the CFD results.

2. Blade design

2.1. Blade element theory

The flow mechanism around a foil is shown in Fig. 1. The value and direction of the relative velocity V_r were determined by both V_w and $R\omega$ which is the velocity for the direction of rotation. The V_r should be designed to match the incidence angle to the optimum angle of attack. The blade pitch angle θ is determined by the incidence angle and angle of attack. The incidence angle also depends on the span along the blade. Thus, the twist angle changes continuously with radial position.

Relative velocity generates the lift and drag forces, which can be divided into a radial force and a thrust that is perpendicular to the disk. The radial force generates the torque that drives the shaft, and the thrust is the primary force causing the bending of the blade. Thus, the thrust should be considered in the structural design.

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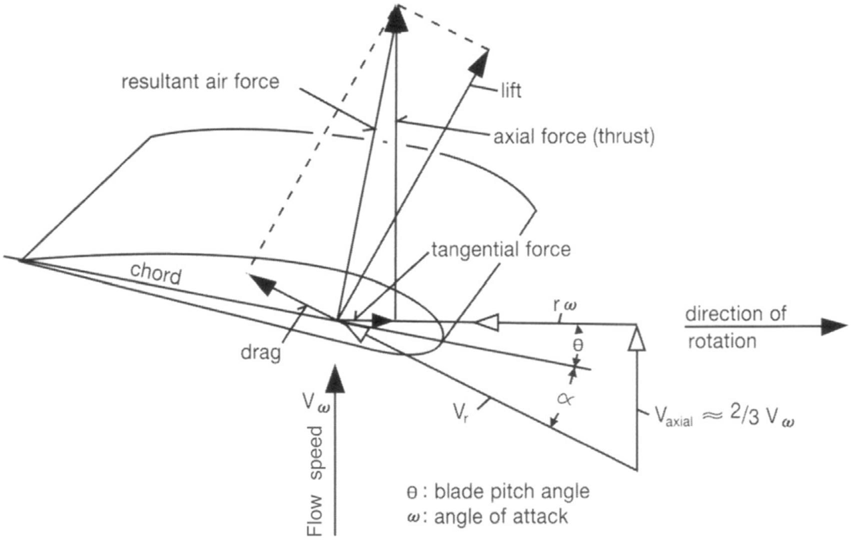

Fig. 1. Flow mechanism around blade element.

2.2. Determination of design variables

The blade design involves a sequence in which specific foils are arranged with appropriate twist angles and chord lengths. The foil should be chosen or determined prior to the design of the blade. To ensure structural integrity, a thick foil of S814 was considered, which was applied to the tidal current device of Seagen developed by Marine Current Turbines (MCT). Fig. 2 shows the shape of the S814 foil.

Blade design is started by the determination of key variables including rated power, current velocity at the site, diameter, and rated RPM. The maximum velocity in Korea is approximately 6 m/s, and design velocity was assumed to be 5.5 m/s. The remaining design variables can be calculated using Eqs. (1) and (2). P in Eq. (1) represents the power capacity, which can be defined as the product of generated power from the turbine and the efficiency of power train η. The target power capacity is 300 kW in this study, and η was assumed to be 0.85. The D represents the diameter of the turbine, which affects both the rated power and the rotational speed. The diameter for the target capacity was calculated by assuming the efficiency of the turbine to be 0.4.

$$P = \frac{1}{8}\rho\pi D^2 U_\infty^3 C_P \eta \tag{1}$$

$$\mathrm{TSR} = \frac{U_{\mathrm{tip}}}{U_\infty} = \frac{D_\omega}{2U_{\mathrm{d}}} \tag{2}$$

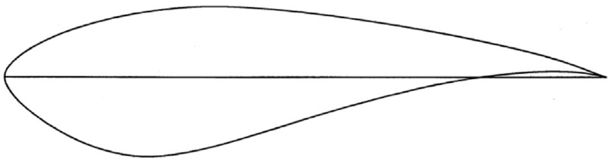

Fig. 2. Profile of the S814 foil.

2.3. Blade tip loss

Since the turbine is driven by the lift force from the foil, tip losses caused by tip vortices are incurred. Eq. (3), suggested by Ludwig Prandtl in 1919, can be used to estimate the loss as follows:

$$f_{\mathrm{t}}(\mu) = \frac{2}{\pi}\cos^{-1}\left[e^{-\{(N/2)(1-\mu)/\mu\}\sqrt{1+(\lambda\mu)^2/(1-a)^2}}\right] \tag{3}$$

The axial flow induction factor was applied for an initial value of 1/3 induced by the Betz limit as an ideal value, and the optimum factor was estimated by using repeated calculations. The chord lengths and twist angles at each span were calculated using the optimum induction factor.

2.4. Chord length and twist angle

The chord length can be determined using Eq. (4) with lift coefficient C_L, number of blades N, a design tip speed ratio (TSR) of λ, flow induction factors (a, a'), and the local span position μ. The chord length, calculated using Eq. (4), rapidly increases close to the hub. In general, in order to reduce production and material costs, the distribution of the chord length is simplified as shown in Fig. 3 since an area of 30% from the tip is dominant for blade efficiency.

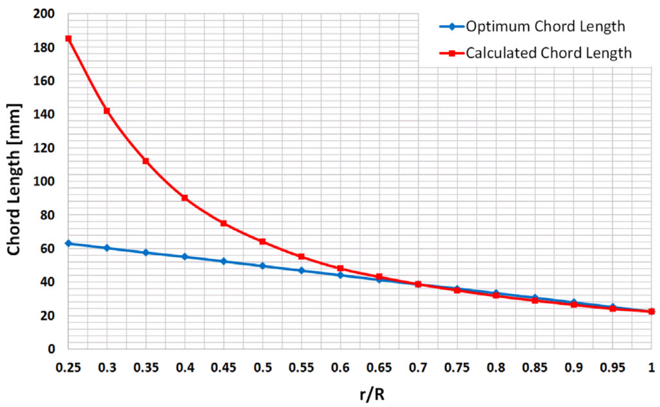

Fig. 3. Distributions of chord length.