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The effect of blockage on tidal turbine rotor design and performance

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A R T I C L E I N F O

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A B S T R A C T

The performance-enhancing effects of closely packing tidal turbines in single row arrays (tidal fences) are evaluated in this computational study. Infinitely long tidal fences are simulated with a range of lateral rotor spacings using a blade element momentum method embedded in a Reynolds averaged Navier–Stokes solver (RANS-BEM).

First, a rotor design tool is applied to determine a hydrodynamically optimal rotor design for each lateral spacing. In the RANS-BEM method, the effect of blockage (the ratio of rotor swept area to channel cross-sectional area) on rotor optimization is accounted for. Increased blockage is found to result in increased optimal solidity and decreased optimal pitch. Next, each rotor design is simulated in its design spacing as well as several off-design spacings. The resulting power coefficient is largest when the rotor optimized for the highest blockage case operates in the array with the closest lateral spacing. Further, although a rotor's performance is improved through operation at a blockage higher than its design point, it still exhibits inferior performance relative to a rotor designed for that higher blockage. The results indicate that blockage must be considered in the rotor design process if the optimal rotor efficiency for a given spacing is to be achieved.

1. Introduction

Unlike most wind turbines, tidal turbines will operate in partially blocked conditions, for instance in a tidal channel, in which the seabed and sea surface are close to the turbine, and/or a closely spaced array, in which the flow is confined by neighbouring turbines. While actuator disc theory predicts the maximum power coefficient for a rotor operating in unbounded flow, also known as the Lanchester–Betz limit, to be $C_{p,Betz} = 0.593$ [1,2], it is widely understood that the Lanchester–Betz limit may be exceeded by operating a rotor in blocked conditions [3]. Despite the prospective performance improvements, however, the effects of blockage on optimal rotor design are not well understood. Although blockage corrections have been introduced for tidal turbine modelling (for instance in analytical blade element momentum (BEM) models [4]), rotors are not generally designed with regard to the blockage conditions the rotor is expected to face in operation.

BEM methods embedded in Reynolds-averaged Navier–Stokes computational fluid dynamics (CFD) solvers, also known as RANS-BEM methods, are particularly well-suited for designing rotors for operation in specified blockage conditions, as well as for the investigation of performance comparisons of specific rotor designs. First, the steady-state solution allows for a relatively fast design iteration and gives BEM methods a computational advantage over unsteady methods of rotor analysis such as actuator line and 3D blade-resolved methods. Second, unlike actuator disc methods, which model the rotor as an idealised disc, BEM methods include the influence of the blade geometry. Finally, the advantage of this method over simple analytic BEM methods is that the flow constraints (such as blockage and boundary conditions) and the presence of supporting structures can be accounted for through the CFD model. However, an assumption of fixed mass flow rate through the domain is maintained.

In this computational study, a RANS-BEM method [5] is employed to evaluate the effects of blockage on rotor design and to investigate the improvement in the rotor power coefficient when tidal turbines are closely spaced in tidal turbine fences. First, the RANS-BEM rotor optimisation tool is utilised to determine hydrodynamically optimal rotor designs for infinitely long tidal fences with lateral intra-rotor spacings ranging from $0.25d$ to $4d$ (d is the rotor diameter), as well as a virtually unblocked case, which is included for comparison purposes. Next, the results of RANS-BEM simulations in which the rotor designs are tested in both design and off-design blockage conditions are presented.

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2. Methods

2.1. Reynolds-averaged Navier–Stokes equations

The Reynolds-averaged Navier–Stokes (RANS) equations are time-averaged representations of the continuity and momentum equations which govern fluid flow (i.e. Navier–Stokes equations) and are

$$\nabla \cdot u_i = 0 \tag{1}$$

and

$$\rho \frac{\partial}{\partial x_j}(u_i u_j) = \frac{\partial}{\partial x_j}\left[-p\delta_{ij} + \mu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)\right] + \rho\frac{\partial}{\partial x_j}\left(-\overline{u_i' u_j'}\right), \tag{2}$$

respectively, for steady, incompressible flow. Here, ρ is the fluid density, u_i is the velocity component ($i = 1,2,3$), μ is the molecular viscosity of the fluid, p is the pressure, and δ_{ij} is the Kronecker delta. A turbulence closure must be employed to model the $-\overline{u_i' u_j'}$ term, which represents the Reynolds stresses, in order to close the RANS equations. The $k-\omega$ shear stress transport (SST) turbulence closure, introduced by Menter [6], is used to close the steady-state, incompressible RANS equations for all simulations in the current work.

The SIMPLE algorithm for pressure–velocity coupling, with an algebraic multigrid method, is employed in the current work. The convective and diffusion terms of the momentum equations are discretised using a second-order upwind scheme and a second-order accurate central differencing scheme, respectively.

2.2. RANS-BEM method and design tool

Analytical blade element momentum methods are based on concepts introduced in the 1920's [7–9] and provide a well-established means of analysing and designing wind turbines [10]. However, traditional analytical BEM methods do not adequately account for the blockage effects that must be considered in the case of tidal turbines.

The present study was therefore competed using an in-house RANS-BEM code and design tool embedded in ANSYS Fluent. The code has been verified and used in the design and simulation of unducted and ducted tidal turbines [5,11]. In addition, Belloni [12] verified the current RANS-BEM code by comparing power and thrust coefficients computed for a bare rotor with those computed using analytical BEM methods for the same rotor. Similarly, Schluntz [13] found good agreement in power coefficient and radial variation of angle of attack for RANS-BEM and actuator line simulations of a rotor operating in blocked flow.

In the RANS-BEM methods, the RANS solver passes the local velocity at the rotor blade elements to the coupled BEM code, which then computes the relative velocity and blade attack angle, and hence the force vector, for each blade element, thereby allowing for the influence of the array effects on the flow to be included in the simulations. An iteration proceeds in which the blade forces, as calculated in the BEM code, and resultant flow field are alternately updated until a converged solution is obtained. RANS-embedded BEM methods have been applied to the study of tidal turbine flow in a number of studies, for instance in Masters et al. [14], Bai et al. [15], and Malki et al. [16].

In RANS-BEM simulations, the rotor is represented as a thin disc. The effects of the forces applied by the rotor on the flow are replicated in the computational domain in the present work by the implementation of a static pressure jump, Δp, across each rotor disc element and the specification of a swirl velocity, u_θ, on the downstream side of each rotor disc element:

$$\delta p = \frac{1}{2}\rho U^2 \sigma(r)(C_l \cos\phi + C_d \sin\phi) \tag{3}$$

$$u_\theta = \frac{U^2 \sigma(r)(C_l \sin\phi - C_d \cos\phi)}{4u_x}. \tag{4}$$

u_x is the streamwise velocity component and ϕ is the flow angle (the angle between the rotor plane and the relative velocity vector, $\mathbf{U}$, at the blade segment). C_l and C_d are the sectional lift and drag coefficients, respectively, for the blade segment and are determined from experimental data tabulated as a function of the angle of attack. The solidity, $\sigma(r)$, at local radius r is dependent on the number of blades, N, and the local chord, $c(r)$:

$$\sigma(r) = \frac{Nc(r)}{2\pi r}. \tag{5}$$

The magnitude of the relative velocity at each blade section is

$$U = \left[(\Omega r - u_\theta)^2 + u_x^2\right]^{1/2}, \tag{6}$$

where Ω is the angular velocity of the rotor and is determined from the tip speed ratio (which is an input of the model).

Prandtl's tip correction [17,9] is included to account for the influence of the unsteady wake structures that form as a result of discrete blades and can not be directly modelled in BEM methods. The tip correction factor, F, is applied to the axial induction factor and is given by

$$F = \frac{2}{\pi} cos^{-1}\left[exp \frac{N\left(1 - \frac{R}{r}\right)}{2sin\phi} \right], \tag{7}$$

where R is the outer radius of the rotor.

The RANS-embedded BEM design tool allows for a tidal rotor to be designed for optimal performance in specified operating blockage conditions. The method iteratively adjusts the sectional chord and twist for each annulus of the blade in order to achieve the maximum power coefficient, C_p, for an assigned tip speed ratio, λ, and target local thrust coefficient, c_x:

$$c_x = \frac{\delta F_x}{\frac{1}{2}\rho \delta A u_x^2}, \tag{8}$$

where δF_x is the magnitude of the streamwise force on a corresponding rotor disc element of area δA. The optimum twist for each blade section is the twist required to maintain the angle of attack, α, that maximises the lift to drag ratio for the given blade section. This value of α is determined from tabulated aerodynamic data and is set as a design angle of attack by the user. While the blade twist is primarily associated with the angle of attack, the blade solidity is primarily associated with the local thrust. Therefore, in order to define the rotor geometry, a design local thrust is also set by the user.

Thus, the in-house RANS-BEM code and design tool used in this study requires the tip speed ratio, λ, target constant local thrust coefficient, c_x, and angle of attack corresponding to the maximum lift to drag ratio for the aerofoil section to be defined by the user. In the design optimisation process, the solidity and blade twist are iteratively adjusted for constant, user-defined values of c_x, λ, and