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Hydrodynamics of marine current turbines

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Abstract

Various global studies have shown that marine currents have large potential as a predictable sustainable resource for commercial scale generation of electrical power. For successful exploitation of this resource, an understanding of the hydrodynamics of the marine current turbine is of primary importance. Although a lot can be learned from the technology transfer from wind turbines and ship propellers, there has been limited hydrodynamics research for this particular application. A methodology is presented for the hydrodynamic design of horizontal axis marine current turbines. Recent research has investigated the performance of suitable 2D section shapes both experimentally in a cavitation tunnel and with numerical simulations. A numerical model of a typical 3D rotor is used to demonstrate parametric variations of the design parameters and the use of alternative blade sections.

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1. Introduction

The utilisation of marine current turbines offers an exciting proposition for the extraction of energy from marine currents [1,2]. The success of using marine turbines to tap the ocean currents is dependent on predicting their hydrodynamic performance. Methodologies need be established which will describe the physical and operational performance of the turbines, allowing their design to be investigated and performance evaluated. Much can be transferred from the design and operation of wind turbines [3]. There are, however, a number of fundamental differences in the design and operation of the marine turbine, which will require further investigation, research and development. Particular differences entail changes in Reynolds number, different stall characteristics and the possible occurrence of cavitation. Much information is however available on the cavitation and stall characteristics of marine propellers [4], which can provide a useful starting point for the investigation of marine turbines.

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2. Hydrodynamic design of marine current turbines

The hydrodynamic design parameters basically entail the choice of diameter, pitch and revolutions for a particular application. Further design criteria include the pitch or twist distribution across the blade span, the stall characteristics, choice of blade section and the need to preclude the occurrence of cavitation. The hydrodynamic design is further complicated by changes in the non-uniform speed and direction of the current, the shear profile in the tidal flow, and the influences of water depth and the free surface.

2.1. Performance prediction

The basic performance of a marine current turbine, like a wind turbine, can be modelled satisfactorily using blade element momentum (BEM) theory [5,6]. This results from the use of high aspect ratio blades for which the resulting flow is close to 2D over the blade sections before stall. In BEM theory, the performance of a part of the rotor between radius (r) and radius ($r+\delta r$) is analysed by matching the blade forces generated by the blade elements (as two-dimensional lifting foils) to the momentum changes occurring in the fluid flowing through the rotor disc between the radii. The local blade forces are solved using the local chord, twist, lift and drag data for the given section.

Some suitable section data is applicable from wind turbines [7] and recent cavitation tunnel tests [8]. For the numerical predictions of section performance used in this study, the 2D panel code XFoil [9] was used. XFoil is a linear vorticity stream function panel method with viscous boundary layer and wake model, and is found to be suitable for producing cavitation criteria at the preliminary design stage [8].

2.2. Section design

Section shape is governed by the hydrodynamic performance and structural design. Like a wind turbine, in order to operate over a wide range of conditions, a wide range of lift coefficient (C_L) is desirable, with delayed separation and stall. In the case of a marine current turbine, it is also desirable that the section shape is such that cavitation inception is delayed. From an efficiency point of view, a low drag coefficient (C_D) is also required. Structural requirements, however, tend to lead to relatively thick sections, particularly near the root, with ensuing higher drag coefficient.

Typical pressure distributions using XFoil for two NACA sections with thickness ratio occurring typically towards the tip are shown in Fig. 1. The NACA 63-215 (Fig. 1a) is commonly used with wind turbines and the NACA 63-815 (Fig. 1b) is a derivation with four times the camber. This increase in camber greatly reduces the minimum pressure (C_P) for a given C_L, which is desirable from the point of view of cavitation. The peaks in the pressure distribution can be used to predict cavitation inception.

Cavitation inception is assumed to occur on the section when the local pressure on the section falls to, or below, the vapour pressure of the fluid, and can be predicted from the pressure distribution [4]. A cavitation number σ is defined as:

$$\sigma = \frac{\left(P_{AT} + \rho g h - P_V\right)}{0.5\rho V^2}, \tag{1}$$

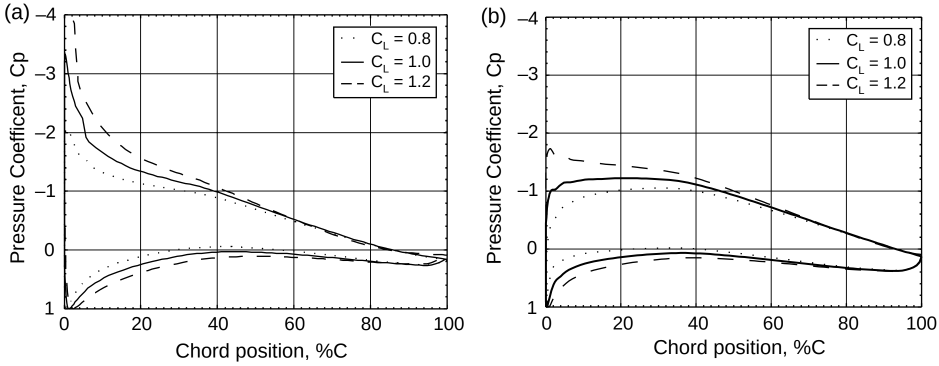

Fig. 1. (a) XFoil predictions for NACA 63-215. (b) XFoil predictions for NACA 63-815.

where P_{AT} is atmospheric pressure (typically 101320 N/m^2), ρ is density (typically 1025 kg/m^3 for salt water), h is the depth of immersion, P_V is the vapour pressure (typically 2000 N/m^2) and V is the local inflow velocity.

The pressure coefficient is defined as

$$C_P = \frac{(P_L - P_0)}{0.5\rho V^2}, \tag{2}$$

where P_0 is the free stream pressure and P_L is the local pressure around the foil. Cavitation inception can be predicted from the pressure distribution since cavitation will occur when $P_L = P_V$, or the minimum negative pressure coefficient $-C_P$ is equal to σ. The cavitation characteristics for a particular section can be described by a minimum pressure envelope or cavitation free bucket, as a function of the section cavitation number. Since, the section lift coefficient C_L is a function of the pressure distribution then, for a particular section, the cavitation-free bucket can be represented as a limiting C_L envelope to a base of σ, Fig. 2.

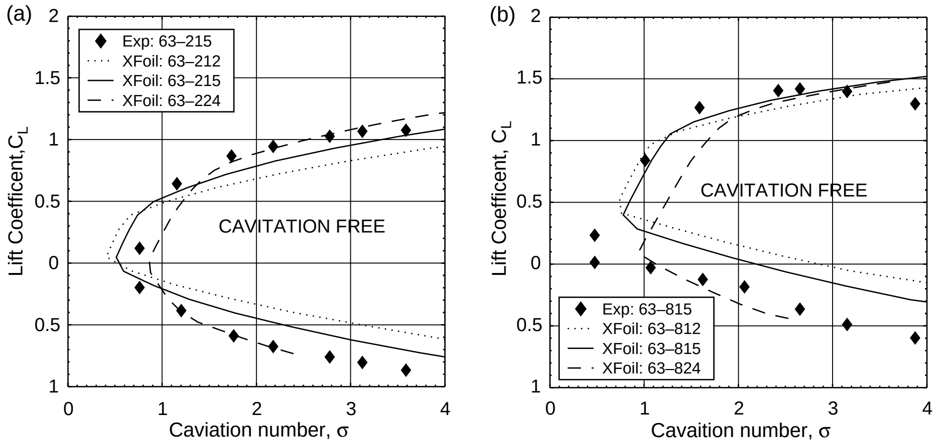

Fig. 2. (a) Cavitation inception bucket for NACA 63-2xx series sections. (b) Cavitation inception bucket for NACA 63-8xx series sections.

Fig. 2 shows the cavitation-free buckets for NACA 63-2xx and 63-8xx sections, with thickness chord ratio, *t*/*c*, of 12, 15 and 24%. The XFoil theoretical estimates for the NACA 63-215 and 63-815 sections are also compared, in Fig. 2, with the experimental data [8]. These show reasonable agreement with the experiments except for the off design case of negative C_L, where inception is under estimated. Both sections show a general increase in the operating region with increase in thickness ratio. It is seen that with knowledge of such characteristic cavitation information, the section shape, chord and local twist can be arranged, whereby cavitation is minimised or avoided.

3. Performance characteristics

Use can be made of the BEM theory and suitable section characteristics to predict the performance of the marine current turbine. The results of a preliminary numerical analysis demonstrating typical performance characteristics are shown in Figs. 3–8.

Fig. 3 shows the assumed blade design parameters for a three bladed turbine. The chord radius ratio, *c*/*R*, was assumed linear from 0.125 at $x=0.2$ to 0.05 at the tip. The thickness, *t*/*c* was also varied linearly from 24% at $x=0.2$ to 12% at $x=1.0$. The overall twist was defined as $\theta = a\tan(1/4\pi x)+\theta_A$. For the NACA 63-2xx series, $\theta_A=2°$ and for the NACA 63-8xx series $\theta_A=-2°$. The difference in angle of 4°, at the same lift coefficient, is due to the change in effective camber as shown in Fig. 4. This figure shows typical XFoil lift and drag predictions used in the BEM calculation for both the NACA 63-2xx and NACA 63-8xx series sections, where xx denotes the *t*/*c* as a percentage. Predictions for $t/c=12$ and 24% are shown and data for $t/c=15$, 18 and 21% were also used in the calculations but are not presented.

The power coefficient for both series of sections is shown in Fig. 5 for pitch angles of 0 and 8°. Both section shapes have similar performance although the NACA 63-8xx series show delayed stall at low tip speed ratio (TSR). Assuming a 15 m rotor and a design speed of 2 m/s operating at peak tip speed ratio (TSR=4.3) results in an operating rpm of 10.9. Based on the BEM

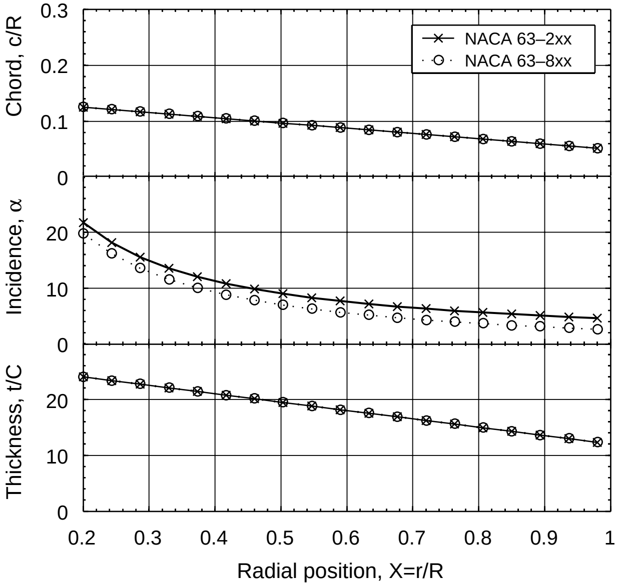

Fig. 3. Blade shapes used in predictions.

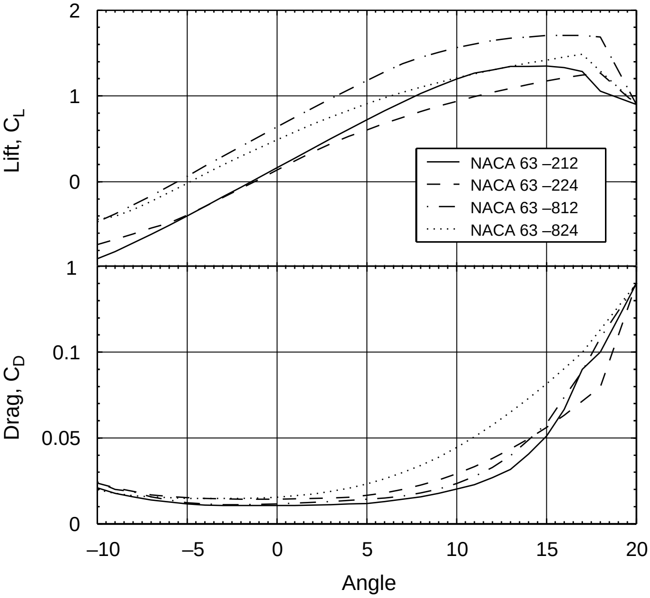

Fig. 4. Typical XFoil 2D lift and drag data.

calculation, typical power predictions are presented for the four cases in Fig. 6. This again reflects the stall delay at tidal flows greater than about 2.5 m/s at 0° pitch.

In order to assess the possibility of cavitation, an off design case with a tidal speed (U_0) of 3 m/s and a depth (h) at low tide of 2 m and 10.9 rpm were assumed. The span-wise distribution

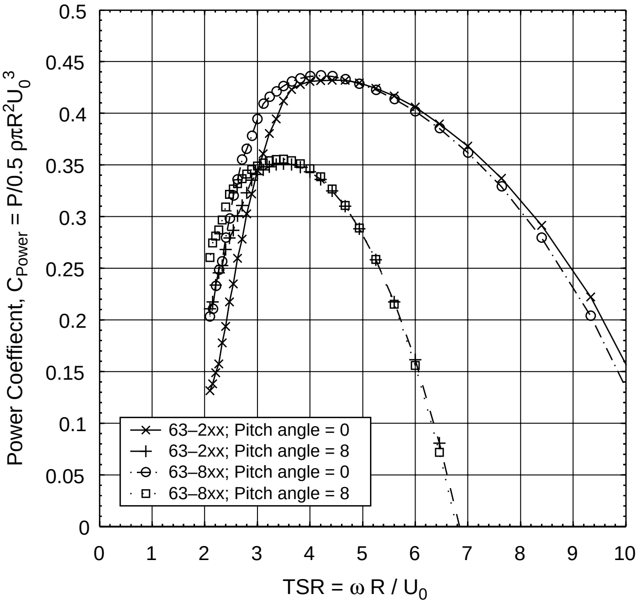

Fig. 5. Rotor characteristics for the two section shapes at two pitch angles.

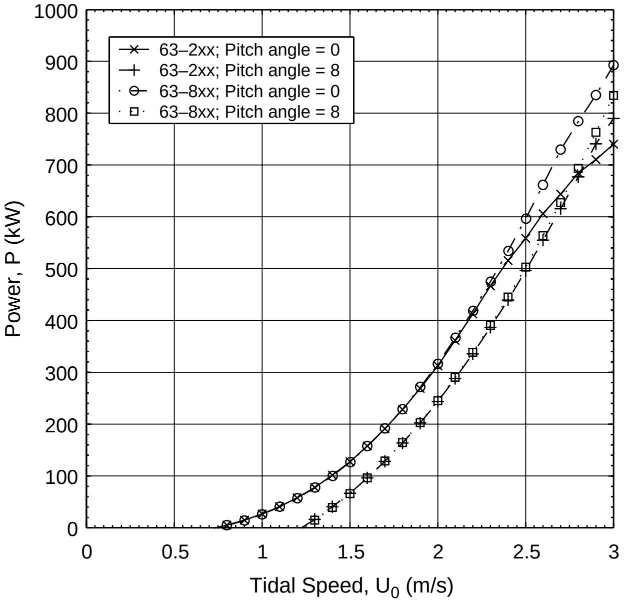

Fig. 6. Power predictions based on a design of 10.9 rpm for 15 m rotor.

of C_L is shown in Fig. 7 and cavitation number in Fig. 8. The cavitation numbers were based on Eq. (1) and calculated with the blade at top dead centre. The C_L and σ values from Figs. 7 and 8 (say at $x=0.9$), can be applied to the cavitation envelopes in Fig. 2. It is seen that the NACA 63-2xx section blade at 0° pitch is likely to suffer some cavitation on the outer parts of the blade,

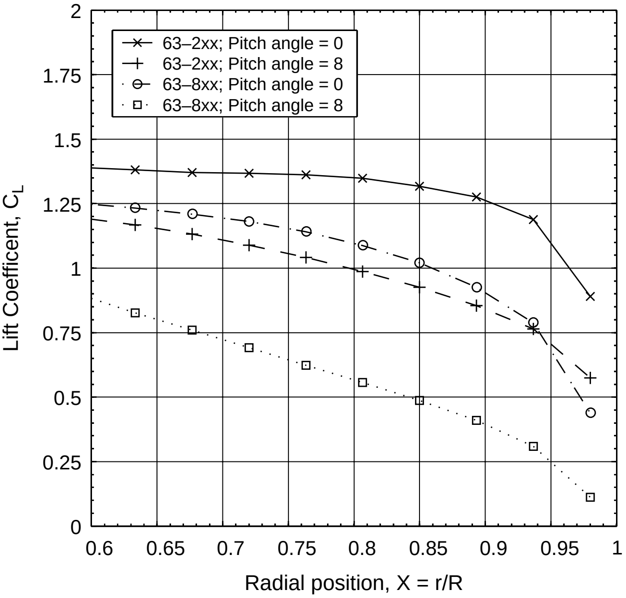

Fig. 7. Lift coefficient distribution at 3 m/s.

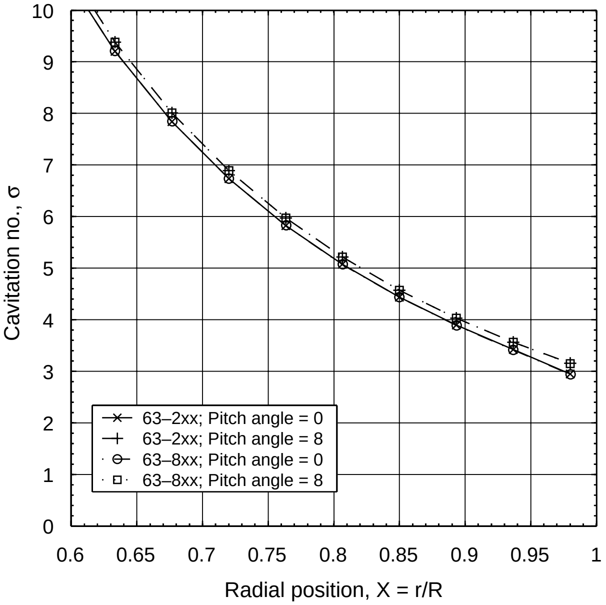

Fig. 8. Cavitation number distribution at 3 m/s.

whilst the NACA 63-8xx section is cavitation free. This demonstrates how cavitation can be avoided or minimised by suitable pitching of the blades or using a section with higher camber.

4. Conclusions and recommendations

An outline of a method for the hydrodynamic design of marine current turbines has been presented. Due to the narrow blades and near 2D flow, the turbine can be modelled successfully using blade element momentum theory. It is noted that suitable section performance data, which also include cavitation characteristics, are required for the detailed design of the marine current turbine blades.

This investigation demonstrates how blade pitch angle or changes in camber alter stall performance and delay the possibility of cavitation for marine current turbines. However, levels of acceptance of cavitation are currently not yet clear. For example, for marine propellers, quite a significant amount of cavitation can be tolerated without significant loss in performance. Such an approach might be adopted for marine current turbines, but cavitation erosion performance for suitable blade materials, such as fibre reinforced plastics, would need to be established.

In a complete investigation, the performance predictions will also include modification to twist/pitch to account for a non-uniform inflow (tidal profile and waves), changes in thickness (hence C_D) for structural purposes and performance in yawed flow during tidal changes.

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