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Numerical optimization and experimental validation for a tidal turbine blade with leading-edge tubercles

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A B S T R A C T

Recently the leading-edge tubercles on the pectoral fins of humpback whales have attracted the attention of researchers who wish to exploit this feature in the design of turbine blades to improve the blade performance. The main objective of this paper is therefore to make a further investigation into this biomimetic design inspiration through a fundamental research study involving a hydrofoil section, which represents a straightened tidal turbine blade, with and without the leading-edge tubercles, using computational and experimental methods.

Firstly a computational study was conducted to optimise the design of the leading-edge tubercles by using commercial CFD code, ANSYS-CFX. Based on this study the optimum tubercle configuration for a tidal turbine blade with S814 foil cross-section was obtained and investigated further. A 3D hydrofoil model, which represented a "straightened" tidal turbine blade, was manufactured and tested in the Emerson Cavitation Tunnel of Newcastle University to investigate the effect of various tubercle options on the lift and drag characteristics of the hydrofoil. The experiments involved taking force measurements using a 3-component balance device and flow visualisation using a Particle Image Velocimetry (PIV) system. These tests revealed that the leading-edge tubercles may have significant benefits on the hydrodynamic performance of the hydrofoil in terms of an improved lift-to-drag ratio performance as well as reducing the tip vortex which is main cause of the undesirable end-effect of 3D foils. The study explores further potential benefits of the application of leading-edge tubercles on tidal turbine blades.

1. Introduction

The humpback whale is a species of giant marine mammal, ranging from 12 to 16 m long. In spite of its large size this creature is unique in its ability to do athletic manoeuvres, especially in catching its prey, compared to other similarly sized marine mammals. Humpback whales utilize their unusually long pectoral fins to perform tight turns to drive a school of fish into a small circular zone so that they can swallow their prey all together. Close observation of their long fins indicates that the leading edges of these fins are not smooth, having some tubercles which are round shape protuberances [1,2]. Wind tunnel tests showed that placing leading-edge tubercles on foils could improve the foil performance in terms of delayed stall and higher lift-to-drag ratio [3–8].

A number of numerical and experimental investigations has been conducted to understand the tubercle concept [8–12]. Some of these investigations indicated that the effects caused by the tubercles on the performance of a 2 dimensional (2D) foil and 3 dimensional (3D) foil are quite different [3,5,6,9,11,13–15]. Studies on the 2D foils were more focused on the optimization of the sinusoidal shape tubercle profiles defined by different parameters. Optimised tubercle profiles on these 2D sections could improve the lift coefficient curves further by maintaining the lift after the stall point. However this was at the cost of a reduction in the maximum lift coefficients since the drag coefficients were increased by these tubercles, at the same time. On the other hand, different performance characteristics have been reported based on the investigations with the leading-edge tubercles on 3D foils which are usually tip tapered like rudders, stabilizer fins, wings, flippers etc. The investigations with the 3D foils also claim the improvement of the lift coefficient curves by maintaining the lift beyond the stall point which is similar to the effect of tubercles on 2D foils. However, in addition to this, the performance regarding to the lift-to-drag ratio can be enhanced [6–8,11,16,17].

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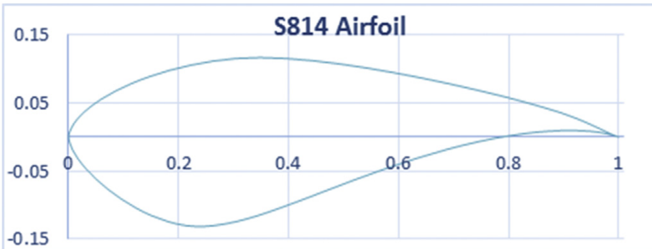

Fig. 1. Cross-section profile of S814 [19].

Fig. 2. Scaled tidal turbine model mounted on the dynamometer of Emerson Cavitation Tunnel [19].

Encouraged by the previous investigations into tubercle performance, especially for the 3D foil applications, an attempt was made recently to apply the tubercle concept to tidal turbine blades and scaled turbine models with different tubercle designs were tested in a towing tank [18]. Some performance improvement was demonstrated in this application even though the power coefficients achieved were not comparable to state-of-the-art levels due to various design and other issues developed during the tests. The blade with only a 1/3 of the span covered with tubercles displayed the best performance amongst the different ranges of the tubercle extensions over the blade span. Based on the results of this recent research it was thought that, there was a scope for further research and development in this field to improve the performance of a tidal turbine and demonstrate it in a validated manner.

The main objective of this study is therefore to make a further contribution to the understanding of the tubercle concept in the design of tidal turbine blades by using computational and experimental approaches. Within this framework, a fundamental investigation using a single 2D and 3D blade configuration is presented in this study. This is intended to achieve some basic understandings of the leading-edge tubercles on a straightened turbine blade prior to applying them to the real blades of a whole tidal turbine.

In the remainder of this paper, an optimization study is presented in Section 2 to optimise the main parameters of the leading-edge tubercles for a single blade with S814 cross-section profile by using the commercial CFD software, ANSYS-CFX. In this exercise a reference 2D foil fitted with different sizes of tubercles was analysed to lead on to the design of a 3D foil with tubercles. Then a straightened 3D foil based on a tidal turbine blade with the same chord length distribution but with a constant pitch angle was designed by using the optimised tubercles and a physical model based on this design was tested in a cavitation tunnel as presented and discussed in Section 3 of the paper. Finally main conclusions obtained from the study are presented in Section 4.

2. Tubercle design and optimization

2.1. Description of tubercle design

The design study was based on a previous UK National research programme (EPSRC-RNET), in which a tidal turbine was designed based on the S814 profile cross-section from the NREL series, as shown in Fig. 1 from Wang et al. [19] who conducted an experimental investigation into the efficiency, slipstream wash, cavitation and noise characteristics of this turbine. The scaled turbine model is shown in Fig. 2 as mounted on the open water dynamometer of the Emerson Cavitation Tunnel of Newcastle University. A representative and straightened version of this turbine blade, which is based on the S814 profile cross-section, was considered as the reference foil in this study to apply the tubercle concept.

The investigation into the optimization of the tubercle profiles was initiated by systematically changing the Height (H) and the Wavelength (W) of these protrusions based on the sinusoidal form

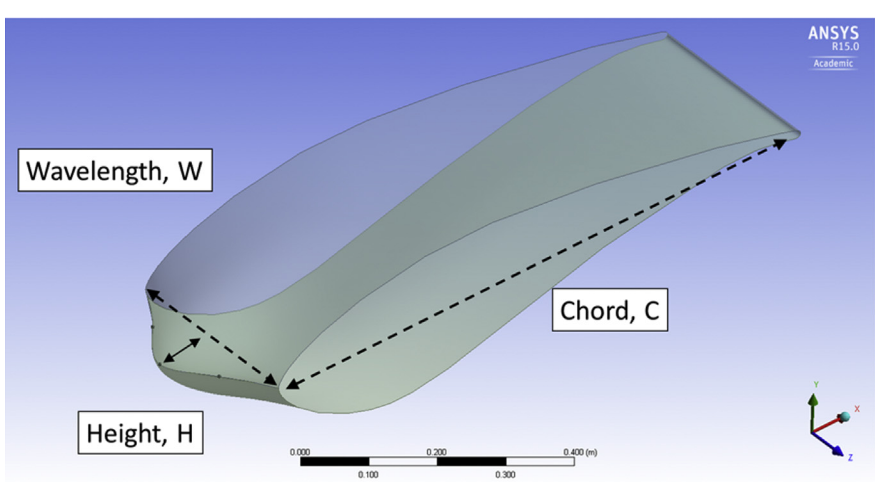

Fig. 3. Definition of 2D foil with a sinusoidal tubercle.