CFD Analysis of the Performance of Blade Cascades for Air Turbines in Oscillating Water Column Wave Energy Conversion Systems

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AERODYNAMICS OF BLADE CASCADES FOR OWC TURBINE APPLICATIONS

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ABSTRACT
This paper presents the results of a detailed CFD (Computational Fluid Dynamics) analysis of the performance of blade cascades in reversing flow axial flow turbines for use as power take-off systems in Oscillating Water Column (OWC) Wave Energy Conversion (WEC) systems. In the first part of the paper a fundamental CFD analysis of the lift and drag data for various aerofoil profiles, using a number of different turbulence models, is described and quantitative comparisons are made with experimental data previously published by other researchers. The second part of the paper then describes CFD results of the performance of various rotors of air turbines. Of particular interest is the “interference effect” whereby the lift and drag data of a blade in a rotor, or cascade, is different from that of a single, isolated aerofoil. The interference effect is important when blade-element methods are used to determine the performance of air turbines, particularly for optimal sizing of the turbine during design stages. The present CFD results are compared to earlier analytical inviscid flow analysis of the aerodynamic performance of cascades for the first time, and the implications for blade element analysis of turbines are discussed.

INTRODUCTION
Ocean Wave Energy Conversion systems are one of the emerging renewable energy technologies that hold the promise of contributing significant quantities of emissions-free energy to our communities in the medium to long-term. A wide variety of technologies have been proposed to extract the energy from ocean waves ranging from floating structures that flex and recover energy through hydraulic systems, such as the Pelamis wave farm being commissioned off the coast of Portugal (Pelamis, 2008) through to various types of buoy tethered to the ocean floor, eg OPT’s PowerBuoy, (Ocean Power Technologies, 2008). For many years the Oscillating Water Column (OWC) system has been seen as one of the most promising of the wave energy technologies. Full scale examples of such devices have included the Limpet on the Isle of Islay in the UK (Whittaker, 2003), the Pico plant in the Azores (Brito-Melo et al., 2008) and the Oceanlinx plant at Port Kembla, just south of Wollongong, in New South Wales, Australia (Oceanlinx, 2008).

One of the key components in any OWC device is the air turbine that must efficiently harness the energy in the reversing/oscillating air flow through the turbine, which
results from the rise and fall of the free-surface in the OWC chamber (as shown schematically in Figure 1).

![Diagram of an OWC device](image)

**Fig. 1: Schematic of an Oscillating Water Column (OWC) Wave Energy Conversion (WEC) device.**

The challenge to the designer of such air turbine systems is to match the characteristics of the air turbine to the OWC chamber and local wave climate so as to provide the maximum overall collection efficiency of the Wave Energy Conversion (WEC) device. The OWC chamber itself requires a certain “pneumatic damping” to ensure the harnessing of wave energy at maximum hydrodynamic efficiency (see for example Thomas, 2008). Thus the air turbine must provide a pressure drop versus volume flowrate characteristic to match the required pneumatic damping over the wide range of flow conditions that arise during each wave cycle and during longer periods of variation of incoming wave characteristics.

The most popular air turbines used in OWC applications have been axial flow turbines and particularly the turbine invented by Wells (1976). Many variants of the Wells turbine have been analysed and demonstrated practically such as those with variable pitched rotor or stator blades and multiple blade rows (Curran and Gato, 1997). Other types of axial flow turbines have also been proposed and used in OWC plant, notably the Oceanlinx variable pitch turbine which operates at much lower rotational velocities than the Wells turbine, see Finnigan and Auld (2003), for example. Two research groups that have examined the performance of the Wells turbine in detail both experimentally and theoretically have been those at the Queens University Belfast (UK) and the Instituto Superior Técnico (Portugal).

This paper details work by the present authors that is aimed at: a) increasing our understanding of the complex flows that occur in axial flow OWC air turbines; and b) providing methodologies that will allow designers of such devices to optimise the performance of the turbine relative to a particular OWC design and wave climate.
ANALYSIS OF AXIAL FLOW TURBINES FOR OWC APPLICATIONS

Prior to the advent of modern desktop computers the analysis of axial flow turbines was carried out using techniques based on the knowledge of the aerodynamics of "cascades" of that time, which involved a number of assumptions as to the flow in the rotor and a deal of empirical data (see Dixon, 1975, for example). In the 1960's a new approach to axial flow turbine analysis was pioneered by a number of researchers, including Hawthorne and Horlock (1962), whereby the actuator disk/blade element model was used to determine turbine performance in a similar manner to the analysis of un-ducted fans and turbines such as wind turbines. The actuator disk/blade-element methodology in a ducted turbine provides a means to determine the swirl velocity downstream of the rotor and thus the forces on the individual blades found from the lift and drag characteristics of the blades concerned, and hence the pressure drop across the device. Falcão and Gato (1984) from Instituto Superior Técnico were some of the first researchers to apply the actuator disk theory to analysis of the Wells turbine. Today CFD may be used to model the details of the flow in an axial flow turbine, however, this approach is still very time consuming compared to the actuator disk/blade-element and it is difficult to cover a sufficiently large portion of the possible parameter space when seeking to optimise the configuration of a turbine with respect to parameters such as radius, flowrates, rotational speed, etc.

Aerofoils, Cascades and Interference factor

For correct application of the actuator disk/blade-element methodology it is necessary to know the lift and drag data for the series of blades in line on the rotor (ie blades in a cascade, Fig. 2). The aerofoils interact with each other and the lift and drag coefficients are no longer the same as for an isolated aerofoil. The ratio of the lift coefficient of a blade in a cascade, $C_{l,i}$, relative to that of an isolated blade, $C_{l,0}$, is known as the "interference factor", $k_0$.

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Fig. 2: Nomenclature for a cascade of aerofoils with stagger angle, $\chi$, on a rotor of an axial flow turbine, with axial air velocity, $V_a$, and tangential velocity relative to aerofoils, $V_\theta$.
Experimental determination of $k_0$ is extremely difficult and only a very few, small, data sets applicable to turbines used in OWC applications are available in the public domain (e.g. Raganathan, 1988). Thus, most, if not all, researchers analysing the Wells turbine have relied on earlier work by Weinig (1964) who determined an analytical prediction of the interference factor for an infinite, linear cascade of blades of straight-line profiles and infinitesimal thickness using potential flow theory. Weinig’s results showed that the interference factor is independent of the angle of incidence of the air flow on the blades of the cascade and is a function only of the stagger angle, $\gamma$ and solidity, $\sigma = c/s$ (where $c$ is the blade chord length and $s$ is the blade pitch, e.g. from leading edge to leading edge of adjacent blades) and a graph from his paper is reproduced in Fig. 3. For the general case of a cascade with arbitrary solidity and stagger angle Weinig’s inviscid flow analysis provides the following estimate of lift coefficient (prior to stall):

$$C_L = 2\pi k_0 \sin(\alpha_0)$$

(1)

Where $\alpha_0$ is the angle of attack (based on the mean of the velocities upstream and downstream of the cascade) and where $k_0$ is given by a complex set of equations and is shown here in Fig. 3. In the case where the stagger angle $\gamma = 90^\circ$, which is applicable to the case of the Wells turbine, Weinig’s gives the interference factor as:

$$k_0 = \frac{2s}{\pi} \tan\left(\frac{\pi c}{2s}\right)$$

(2)

This equation has been widely used by researchers as the correction factor to be applied for Wells turbines, however, there has been very little, if any, validation of this relationship between $k_0$ and solidity for practical aerofoil cascades. Moreover, the more general relationship between interference factor and solidity for cascades of arbitrary stagger angle (Fig. 3) has received virtually no attention in the public domain literature.

**CFD METHODOLOGY**

The key objective in the present research was to use CFD methods to determine the interference factor for cascades of relevance to OWC axial flow turbines under realistic flow conditions, i.e. assuming viscous, turbulent flow. The first step was to ensure that the CFD analysis was accurate and to this end a large number of initial simulations were carried out on aerofoil profiles with well-known lift and drag characteristics. However, it became clear that much of the previous experimental and CFD data presented by other researchers was not entirely consistent. Over the past few years a number of researchers have investigated earlier experimental aerofoil data sets and compared them with aerodynamic coefficients computed from CFD analyses. Grotton and Bruce (2007), for example, reported considerable discrepancies in the published lift and drag coefficients taken from the different sources and evaluated at comparable Reynolds numbers. The present authors have also carried out a similar review of aerodynamic data for some isolated single aerofoils in the public domain and carried out CFD simulations for the same aerofoil profiles. Initially a large number of simulations of both isolated aerofoils and aerofoils in cascade were modelled using various turbulence
models including the $k$-epsilon, RNG $k$-epsilon, $k$-omega and Shear Stress Transport (SST) models. These were all implemented using the ANSYS CFX CFD code. The simulations that showed the closest match were obtained by applying the $k$-epsilon model. A plot of typical velocities and streamlines for an aerofoil in a linear, "tandem" cascade is shown in Fig. 4, where the technique of "repeating" upper and lower boundaries has been used to simulate the infinite number of blades.

Fig. 3: Prediction of the interference factor (ratio of lift coefficients for blade in a cascade and of an isolated aerofoil) from potential flow theory (Weinig, 1964).

Fig. 4: Typical CFD results of velocity field in a "tandem" cascade of NACA0021 aerofoils with solidity $c/s = 0.5$. Dashed lines are repeating boundaries, scale in m/s.
RESULTS AND DISCUSSION

**Isolated Aerofoil Lift and Drag**

To illustrate the type of results developed from the CFD analysis described above, a comparison between experimental lift data for NACA0012 aerofoil taken from two different sources (Critzos *et al.*, 1955, and Sheldahl and Klimas, 1981) and CFD computed lift coefficients for angles of attack from 0° to 90° is shown in the Fig. 5. Analysis of these data shows that there are three distinguished intervals on each lift curve. In the pre-stall region from approximately 0° to 20° and for the region close to 90° both sets of experimental data and the CFD data match closely. The interval from 20° to 70° is the post-stall region which is notoriously difficult to simulate with any great accuracy, however, the results here, gained after significant refinement of the grid, is reasonably close.

[Graph showing lift coefficient (C_L) vs. angle of attack (deg)]

Fig 5: Example of experimental lift data from different authors showing some for NACA 0012 aerofoils at Re=1.8×10^5 (Critzos *et al.*, 1955) and Re=2×10^6 (Sheldahl and Klimas, 1981) and CFD computed coefficients at Re=2×10^5 in the present study.

**Cascade Analysis and Interference Factor**

One of the few sets of experimental data showing the mutual interference between NACA0021 aerofoils in tandem cascades of three and five blades was reported by Raghunathan (1988). One of the conclusions from that study was that the lift coefficients increase with increasing numbers of blades in a cascade. The present authors have simulated a linear cascade of NACA0021 aerofoils staggered at 90° using the same solidity of 0.5 and with a comparable Reynolds number of 2.5×10^5 (see Fig. 6). It is clear from these results that the CFD simulations produce results that are consistent with the experimental data of Raghunathan, although there are some differences for the five-blade cascade which may be attributed to the significant

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blocking effect that may have occurred in his wind tunnel experiments. These results provide further reassurance as to the effectiveness of the CFD technique as a means of modelling the behaviour of cascades.

A major goal of this phase of our work was to compare, for the first time, the values of \( k_0 \) predicted from Weinig's inviscid flow analysis (as shown in Fig. 3) to those of a full viscous flow CFD analysis. To illustrate one small part of the results from this study we present the interference factors found in our CFD study of a cascade comprising blades similar to those described by Finnigan and Auld (2003) with a NACA 65-418 profile and maximum camber height of 6% and maximum thickness to chord ratio of 18%. This blade section has been proposed by Finnigan and Auld for use in OWC axial flow turbines and is symmetric about the mid-chord and is formed by combining two front halves of the NACA 65-418. Values of lift interference factor \( k_0 \) deduced from the CFD simulations for an approach angle (upstream angle of attack) \( (\beta - \gamma) = 10^\circ \) as a function of stagger angle and solidity is shown for Fig. 7. The results for the drag interference factor \( \delta_k = C_D/C_{D0} \) for the same cascade are shown in Fig. 8. Note that the lift and drag coefficients for the cascades have been calculated using the mean of the upstream and downstream angles of incidence as defined by Weinig (1964).

![Graph showing comparison of experimental data for cascades of three and five NACA 0021 aerofoils (Ragunathan, 1988) and a CFD simulation from the present work of an infinitive number of aerofoils in cascade (\( \sigma = 0.5 \)).

The CFD results for \( k_0 \) in Fig. 7 are the first to be published to the knowledge of the present authors and they show a close similarity to the Weinig inviscid flow analysis results of Fig. 3 although the magnitudes of \( k_0 \) predicted from the CFD analysis are somewhat larger than Weinig's results (for \( s/c < 1.5 \)) possibly due to the increase in velocity around the aerofoils due to the blockage effect from the finite thickness of the
practical aerofoils. Note that the latter also leads to a lower limit to the value of s/c that can be implemented with practical aerofoils.

Fig. 7: Interference factors for lift on a linear cascade of blades similar to that described by Finnigan & Auld (2003) as deduced from present CFD analysis for an upstream angle of incidence $\beta_i = 10^\circ$ (legend gives cascade stagger angle).

Fig. 8: Interference factors for drag, complimenting the results shown in Fig. 7. The results for the drag interference coefficient as a function of stagger angle and solidity are shown in Figure 8 and where a trend of increasing interference factor, $\delta_o$. 

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with decreasing spacing of the blades is observed, as is to be expected. It is to be remembered that this increase is not only the result of the effect of the neighbouring blades but also that increasing solidity results in increased restriction of the axial flow of fluid through the cascade and thus pressure drop (and hence effective drag) increases rapidly as the width of the passages between the blades fall below a chord length. The next stage in the research program is to investigate the application of the interference factors determined above (and for other angles of incidence and blade shapes) to actuator disk/blade-element analysis of axial flow turbines for OWC systems.

CONCLUSION

The paper has outlined a CFD study of the behaviour of single isolated aerofoils and aerofoils in linear cascades that are suitable for use in reversing flow, axial turbines for OWC devices.

The CFD methodology adopted has demonstrated that extremely good agreement between experimental data and the CFD simulations may be obtained for lift coefficients for angles of attack below stall on isolated aerofoils. A review of the literature has shown that experimental data for post stall lift and drag coefficients for given aerofoil sections is often inconsistent. However, acceptable agreement between our CFD analysis results and previous experiments by others has been obtained for post stall conditions for the purposes of engineering design and blade element analysis of axial turbines.

We have reported for the first time a successful attempt to model the interference factors that arise in both lift and drag coefficients when aerofoils are located in linear cascades of infinite length using CFD analysis. We have compared our results with those from Weigl’s inviscid flow analysis (1964) and found that the lift interference factor, $k_0$, in practice is close to Weigl’s. In addition, new results have been presented herein for the drag interference factor, $\delta = C_D/C_{D0}$, which will be useful in applications of blade-element modelling to axial flow turbines for oscillating water column wave energy turbines.

REFERENCES


BRIEF BIOGRAPHY OF PRESENTER
Paul Cooper is an Associate Professor and Head of the School of Mechanical, Materials and Mechatronic Engineering at the University of Wollongong. His research interests are currently focussed in the area of Renewable Energy systems, particularly Ocean Wave Energy Conversion Devices and Small Scale Wind Energy. He is also convenor of the University of Wollongong Energy Futures Network http://research.uow.edu.au/energyfutures.