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A METHODOLOGY FOR THE BLADE SHAPE OPTIMISATION OF A VERTICAL AXIS TIDAL TURBINE UNDER CONSTRAINTS

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ABSTRACT

Hydrokinetic vertical axis turbines have found use in the field of tidal energy exploitation as they can operate under varying flow directions. Due to the vertical rotation axis, the blades undergo continuous variations of the angles of attack, resulting in alternating forces on the turbine structure. This may lead to structural damage and fatigue failure. By actively and continuously pitching the turbine blades, it is possible to reduce these forces and to improve the power coefficient of the turbine. For this reason the OPTIDE project aims at developing a Darrieus turbine with an active, variable blade pitch. A customized actuator will be embedded in the blades for improved flow characteristics. The aim of this paper is to describe the methodology for the optimisation process needed to find the optimal blade shape, suitable to fit the actuation system at quarter chord with best hydrodynamic properties. The optimisation consists of a computational fluid dynamics (CFD) simulation coupled with a Genetic Algorithm (GA). OPAL++, the optimisation software used in this work, outputs ten design variables, which, together with the constraining points of the actuator, describe the hydrofoil shape. These points are imported into a *Python* script to interpolate the full hydrofoil shape with use of a Bézier spline curve, which is then uploaded into the automatised meshing tool. The subsequent numerical simulation provides the power and thrust coefficients of each individual setup, i.e., the objectives of the optimisation.

Keywords: active variable pitch, blade shape optimisation, CFD, Vertical Axis Tidal Turbine

NOMENCLATURE

D	$[mm]$	Diameter
N	$[-]$	Number of blades
P	$[W]$	Power output
P_∞	$[W]$	Power of the flow
R	$[mm]$	Radius
c	$[mm]$	Chord length
c_p	$[-]$	Power coefficient
v_∞	$[m/s]$	Velocity of the free stream
λ	$[-]$	Tip-speed ratio
ω	$[rad/s]$	Angular velocity
σ	$[-]$	Solidity

1. INTRODUCTION

In 2020 a global energy consumption of 556.63 EJ was recorded, from which only 69.87 EJ were covered by renewable energy [1]. In order to achieve the energy transition from fossil to renewable energy it is necessary to increase the amount of renewable energy installed worldwide. The most implemented renewable energies nowadays are wind, solar and hydropower. Out of these, hydropower is independent of weather-dependent fluctuations and therefore represents a reliable energy source. Conventional hydroelectric power plants usually reach high efficiencies by taking advantage of the potential energy of the water [2]. In order to reach sufficient hydraulic head, these water turbines need support structures such as dams. Apart from being cost-intensive, these dams are not environmentally friendly as they alter natural waterways and therefore affect the local ecosystems. In addition the expansion of conventional hydropower is currently stagnating as most of the potential sites worldwide are already being exploited [3].

However, ocean energy is one branch of hydropower which still shows a large untapped potential. It is projected that by 2030 around 10 GW of ocean energy could be installed worldwide [4], out of which until 2020 only 527 MW have been installed [5]. Ocean energy is divided into tidal, wave, salinity gradient, and ocean thermal energy conversion (OTEC) out of which the tidal energy has the highest installed capacity [4]. Tidal turbines work similar to wind turbines as they only use the kinetic energy of the flow. Therefore, these kind of turbines do not need significant support or guiding structures and present easier constructions as well as a lower impact on the environment [6].

Similar to wind turbines, tidal turbines can be classified into two categories: vertical-axis turbines (VAT) and horizontal-axis turbines (HAT). In this project the focus will be set on VAT or so-called cross flow turbines, which have their axis perpendicular to the incoming flow (see Fig. 1) [7]. One of the main advantages of these cross-flow turbines is that they are omni-directional, meaning that they operate independently from the direction of the flow [6, 8]. This characteristic makes them extremely suitable for the operation in tidal currents or unsteady flows [6]. Due to the vertical axis it is also possible to position the electrical drive system above the water level, making it easily reachable for maintenance [9, 10, 11]. One of the most important advantages of hydrokinetic turbines with a vertical axis is that they feature a magnitude higher area-based power density in farm installations compared to HAT [12].

Darrieus turbines, feature bad self-starting characteristics as the angle of attack of each blade varies during one rotating cycle of the turbine leading to stall [9]. Due to the occurring stall on the turbine blades, the rotor also experiences complex rotor dynamics, which lead to high structural loads, vibrations and significantly lower efficiencies compared to HAT [6, 13, 11]. This being one of the biggest drawbacks of Darrieus turbines it is necessary to reduce the occurring stall as much as possible.

Different approaches can be found in order to increase the efficiency of Darrieus turbines. One typical approach of the optimisation process is to change typical geometrical design features, such as the hydrofoil shape as well as the solidity of the turbine [2, 14]. The solidity σ of a turbine comprises the number of blades, the cord length and the turbine radius, and is one of the main parameters used to describe the geometry of a VAT [15]. It is defined by the following equation: $\sigma = \frac{Nc}{R}$, where N is the number of blades, c the chord length of one blade and R the rotor radius. *Shiono et al. (2000)* found in an experimental study that the efficiency of Darrieus turbines for tidal power generation increases with decreasing number of blades N. Meanwhile the starting torque increases with a higher amount of blades, while at the same time torque ripple decreases [16]. In general a global tendency to three-bladed turbines is observed as they feature lower manufacturing costs, less drag force induced by the support structure and a lower torque ripple [2, 17, 11].

By optimizing the hydrofoil shape of a VAT it is possible to increase the turbine efficiency and reduce the occurring stall, which might improve the self-starting capacity of the turbine [9]. *Mohamed (2012) and Hashem (2018)* analysed different symmetric and cambered airfoils for a Darrieus wind turbine with constant solidity in order to increase the overall output power coefficient c_p, which is defined by the ratio between the power output of the turbine (P) and the power of the flow crossing the swept-area of the turbine (P_∞). They both found that the S-1046 profile performs best [15, 18]. Another approach is to couple CFD simulations with an evolutionary algorithm in order to find the best suitable hydro- or airfoil shape for the desired application. *Daróczy et al. (2018)* coupled GA with CFD simulations in order to find the best airfoil shape for an H-Darrieus turbine [19]. *Yang and Shu (2012)* optimised the hydrofoil shape of a helical vertical axis turbine and were able to increase the power output to 41.2%, compared to a classical NACA0012 that only reaches 32.9% [7]. Similar optimisations were done by [20, 21].

Besides varying the number of blades and optimizing the hydrofoil shape, pitching the turbine blades during the turning cycles can eliminate blade stall and therefore increase the turbine efficiency and deliver high starting torque [9]. Pitching can be passive, where the blade is allowed to move freely, or active, where the blade is mechanically driven to a specific angle of attack. *Ridho Hantoro et al. (2011)* found that passive pitching of the blades of vertical axis tidal turbines increases the capability of self rotating, while it decreased the potency of stall [22]. Still, the effect of passive pitching is rather arguable [9]. Otherwise, many studies have shown the effectiveness of active blade pitching and the impact of different pitching laws [11, 10, 8, 6]. For instance, CFD simulations by *Hwang et al. (2009)* showed that a cycloidal pitching motion increases the turbine performance by 70%. Further simulations demonstrated, that an individual blade pitching is able to improve the performance by around 25% compared to the cycloidal pitching motion. Unfortunately, validation experiments with the cycloidal motion revealed quite lower performance values than the simulations. This was due to drag forces of the mechanical pitching device, which featured a central actuator on the turbine shaft with rods as a mechanical transmission to the blades [17]. *Liang et al. (2016)* equipped each blade with a servomotor, which allows the individual pitching of each blade [23]. As the drives are positioned outside of the blade structure they are unfavorable to hydrodynamics, leading again to increased drag forces, which reduce the overall turbine performance.

Although further research on the mechanical implementation of active pitching needs to be done, it can clearly be seen, that individual pitching increases the turbine efficiency and is able to decrease stall, vibration and both torque and thrust ripples [11]. For this reason the OPTIDE project aims at developing a H-Darrieus tidal turbine, which integrates the individual pitching actuator in each blade. Figure 1 shows the current prototype of the OPTIDE turbine. The idea of the project is to explore the effects of an optimised pitch motion law through CFD and experimental research. Besides delivering validation data, flume tank experiments will be performed in order to optimise the pitching law. State-of-the-art instrumentation, providing data describing the turbine performance, will be coupled with an optimisation algorithm in order to achieve an optimal pitching trajectory. As mentioned before, in order to improve flow characteristics the pitching actuator shall be positioned inside each turbine blade. For this reason, the blades are connected to the turbine shaft through two blade support structures (at the top and bottom of the blades). This way it is also possible to have a discontinuous shaft, which does not affect the flow in the cross-section of the turbine.

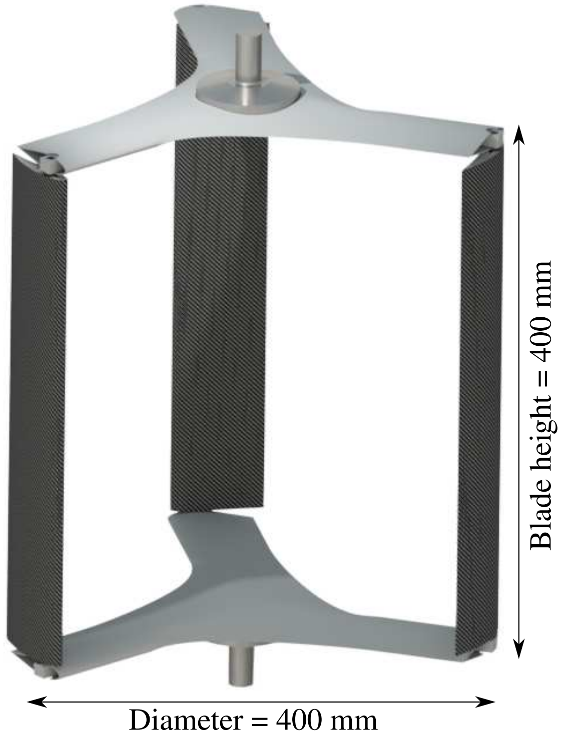

Figure 1. 3D Model of the Darrieus turbine being developed in the OPTIDE project

As shown by *Abbaszadeh et al. (2019)* only a bandwith of 30 to 40 degrees are necessary for the optimal blade motion law [6]. Therefore, a special limited-angle torque motor is being developed for the OPTIDE turbine, which will be able to satisfy the needed pitching range and the required torque [24]. In order to fit the actuator, with a maximum height of 13 mm and width of 35 mm, it is necessary to determine an optimal blade shape in the design process of the turbine model for flume tests and pitching trajectory optimization. The aim of this paper is to present the methodology to be employed in order to find the most suitable blade shape for the turbine being designed as part of the OPTIDE project. This optimisation setup consists of three parts which will be described in detail in the following.

2. METHODOLOGY

As mentioned before, the solidity is a design parameter that describes the correlation between number of blades N, chord length c and rotor radius R. In literature different equations can be found to describe the solidity σ. For this work, the solidity will be described through equation 1:

$$\sigma = \frac{Nc}{R} \tag{1}$$

The tip-speed ratio λ is another important parameter [25]. It describes the ratio between the tangential velocity, which results from the rotating motion, and the inlet velocity v_∞. λ is defined with the following equation, where the tangential velocity is given by the angular velocity ω multiplied with the turbine radius R:

$$\lambda = \frac{\omega R}{v_\infty} \tag{2}$$

The correct combination of λ and σ are very important in order to find the optimal operating point of a turbine. For high solidities the best turbine efficiency is found at low tip speed ratios [19], while at the same time, lower solidities increase the turbine efficiency. Although higher solidities increase the hydrodynamic loads on the turbine, they are often favored as they improve the self-starting ability of the turbine. As hydrokinetic turbines have, compared to wind turbines, less self-starting problems it is possible to lower the solidity in order to increase the efficiency [2, 10]. Darrieus-turbines in tidal energy applications show their highest efficiency at a solidity σ in between 1 and 1.2 and a tip speed ratio λ in between 2 and 3 [16, 13, 10, 6, 26]. As the OPTIDE turbine will be equipped with a blade-embedded pitching actuator it is possible to run the turbine at higher solidities and therefore at lower tip-speed ratios, while still achieving high efficiencies. Stall and vibrations can be mitigated by blade pitching. By lowering the tip-speed ratio blade-blade interactions and mechanical losses will also be reduced.

The turbine designed for the OPTIDE project has a rotor diameter of 400 mm, a blade height of also 400 mm and will be equipped with three blades (see Fig. 1. In order to achieve a solidity $\sigma = 1.2$ a chord length of about 80 mm would be suitable. Due to the size of the blade-embedded pitching actuator, which is 13 mm high and 35 mm wide, it is not possible to use a standard airfoil shape, such as the S-1046 recommended by [15] and [18]. Figure 2 (a) shows the possible design of the pitching actuator embedded at quarter chord of a S-1046 foil with a chord length of 80 mm. It can clearly be seen that the actuator can not fit in the hydrofoil. In order to install the motor in the S-1046 blade, it is necessary to increase the chord length up to around 100 mm (see Fig. 2 (b)) leading to a solidity $\sigma = 1.5$. In this case lower tip-speed ratios are required to reduce blade-blade interactions. This makes it even more necessary to employ a successful blade pitch trajectory for stall mitigation. In consequence the optimal hydrofoil shape will be a trade-off of blade thickness and length along with an adapted λ to satisfy all the requirements.

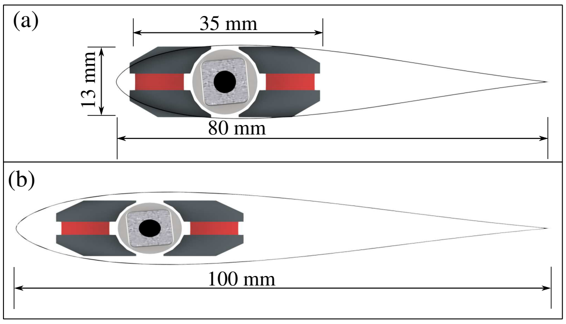

Figure 2. S-1046 hydrofoil with the blade-embedded actuator at the quarter chord for chord length 80 mm (a) and 100 mm (b)

For the given application it is reasonable to perform an optimisation, which allows to test many different hydrofoil shapes by using CFD simulations coupled with evolutionary algorithms. The optimisation consists of three main components: the optimisation software, the numerical simulation and a *Python* script, needed in order to couple the optimiser with the CFD. Figure 3 shows a flowchart describing the optimisation process.

2.1. Optimisation software

A multitude of optimisation methods can be employed in engineering optimisation tasks. Beside analytical solutions of physical models of reduced order, gradient-based methods (e.g. for maximum-power-point-tracking) or evolutionary algorithms (for very complex systems) are mostly used. Gradient-based methods search for the optimum by calculating local gradient information, resulting in an acquired local optimum, which does not always correspond to the global optimum [21, 20]. Genetic Algorithms (GA) on the other hand evaluate the fitness of a population, here a set of different hydrofoils, in order to satisfy a specific fitness function [20]. For this reason GA are more likely to find a global optimum instead of a local optimum [21, 20]. In the framework of this study an in-house genetic algorithm software called OPtimization Algorithm Library++ (short: OPAL++) developed at the Otto von Guericke University Magdeburg [27] will be applied. OPAL++ allows single- as well as multi-objective optimisations and has already successfully been used for many optimisation problems [27, 19, 28, 29].

For this work, a multi-objective optimisation will be performed, with the objectives to maximise the tangential forces and to minimise the normal forces on the blades during one revolution of the Darrieus tidal turbine. This way the power output will be maximised, while the occurring loads shall be kept as low as possible. A minimum of 500 individuals is expected to be analysed during the optimisation process, which will be performed on the cluster at the Laboratoire des Ecoulements Géophysiques et Industriels (LEGI) in Grenoble, France. The hydrofoil shape will be constrained by five points, given by the size of the pitching actuator and the pivot point. OPAL++ will optimise the y-location of eight different points, three at the hydrofoil leading edge, one at the trailing edge and four on the upper and lower hydrofoil surface. Additionally the cord length of the turbine as well as the tip-speed ratio λ will be varied, resulting in ten design parameters. As shown in Fig. 3, the optimisation software, OPAL++, will read the results from the CFD simulation, compare the outcome of the fitness function for the different individuals and create a new set of hydrofoil design parameters, which are derived from the best performing individuals in the previous simulation. These parameters are then read into the *Python* script, as detailed in the next section.

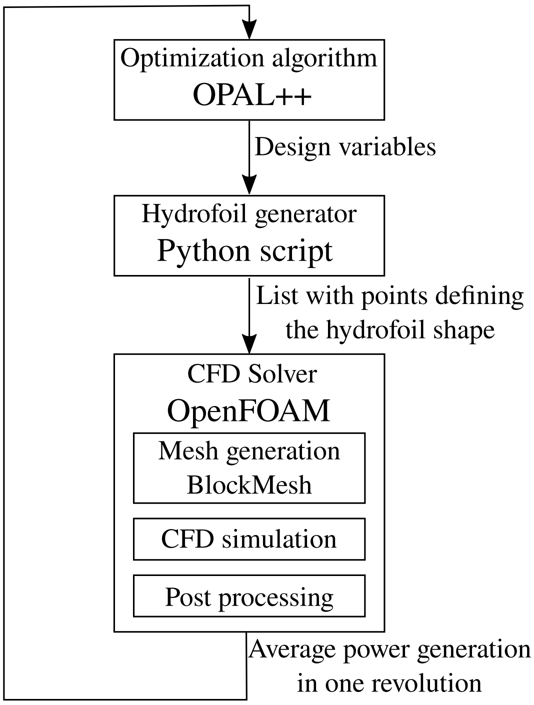

Figure 3. Flowchart of the optimisation

2.2. Hydrofoil shape generation

The optimisation software described above decides on a new set of variables for the hydrofoil shape for the next generation of individuals. The set of variables together with the fixed points, given by the position and size of the motor, define the rough shape of the hydrofoil. A *Python* script processes the given points in order to create a smooth hydrofoil shape. Here the *scypy* interpolation package is used in order to find the B-spline representation of a 1D-curve [30]. The degree of the B-Spline is automatically chosen by the program.

After the spline generation, lists with x- and y-coordinates needed to define the hydrofoil shape are generated. These lists are then converted in order to match the required format for the meshing utility and are then imported into *BlockMesh* in order to create a mesh, which will be described in the following section. Besides creating the spline out of the variable set defined by OPAL++, the *Python* script also creates a plot of the generated hydrofoil, in order to allow the user to visibly check the created shape.

2.3. Mesh generation and CFD simulation

One of the most important steps in order to achieve good and valid results in a CFD simulation is the design of a mesh with a good quality. The CFD simulations will be performed using *OpenFOAM* v2112. For this reason the *BlockMesh* utility, which is part of *OpenFOAM*, will be used in order to create a multi-block structured mesh of the turbine. The two-dimensional computational domain is divided into six sub-domains (see Fig. 4: an outer stator (in yellow), a rotating ring (in green), the three blades (in red) and an inner stator (in blue). In order to get cells with a good quality and refine each section as necessary each sub-domain will be blocked as shown in Fig. 4

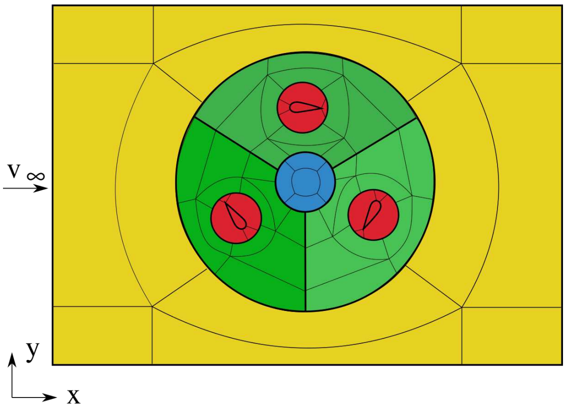

Figure 4. Computational domain and blocking of the mesh. Divided into four subdomains: outer stator (yellow), rotating ring (green), blades (red) and inner stator (blue)

For the first simulation a large outer domain with a length (x-direction) of $45D$ and a width (y-direction) of $60D$ was chosen. The distance between the inlet and the center of the turbine amounts to $15D$. The size of the outer domain will be adapted through a preliminar confinement study, on which the distance from the sides to the center of the turbine will be iteratively reduced.

The sub-domain of the rotating ring is composed by three identical sections with an inner and outer radius of about $2R = 400$ mm and $0.25R = 50$ mm, respectively. One section is meshed and then rotated by 120° and 240° to complete the ring. These sections will then be joined using the *stitchMesh* function of *OpenFOAM*. In the center of the rotating ring sub-domain lies an inner stator, which is meshed using an O-Grid blocking.

The blade sub-domain is located inside each section of the rotating ring. This section of the mesh is highly parametrised in order to adapt correctly to the imported B-spline points from the *Python* script. The grid created with *BlockMesh* is defined in a so-called *blockMeshDict* .txt-file which is automatically edited by the scripts. Each block of the hydrofoil sub-domain is refined to satisfy $y^+ < 1.6$ for a fully resolved boundary layer accordingly to *Maître et al.* [31].

After meshing all the sub-domains, they are subsequently joined using the *mergeMeshes* command in *OpenFOAM*. Between the sliding interfaces of the sub-domains a so-called Arbitrary Mesh interface (AMI) is employed, which maps the flow quantities from one sub-domain onto the adjacent domain with a weighted interpolation function to respect mass conservation. This is necessary due to the rotating motion of the ring sections.

In order to accurately evaluate the averaged performance of the turbine for one revolution, the incompressible Unsteady Reynolds-Averaged Navier-Stokes (URANS) equations will be solved using the open-source software *OpenFOAM*. The $k - \omega\ SST$ (Shear Stress Transport) method is chosen in order to accurately model the turbine. Various studies have found, that this turbulence model is suitable for airfoil and VAT simulations [11, 32]. After the numerical simulations are finished, the *OpenFoam* results are read into a python script using the *FluidFoam package* (https://github.com/fluiddyn/fluidfoam) in order to calculate the tangential and the normal forces [33]. These values are then imported into OPAL++ and analysed, in order to get a new set of hydrofoil design variables for the subsequent generation. This process is iteratively repeated until the optimization converges.

A first simulation has been conducted in order to check that the mesh setup and the simulation parameters are set correctly. 10 revolutions with a step of 1° at a λ of 2 (inlet velocity of 0.8 m/s) were carried out. With the current mesh, consisting of 188.000 cells, the simulation took about 10 hours to calculate. The average power coefficient c_p for the last revolution was equal to 0.347 and the difference in c_p between the last two revolutions was lower than 0.5%. Figure 5 shows the velocity field in the vicinity of the turbine at the last time step (10th revolution).

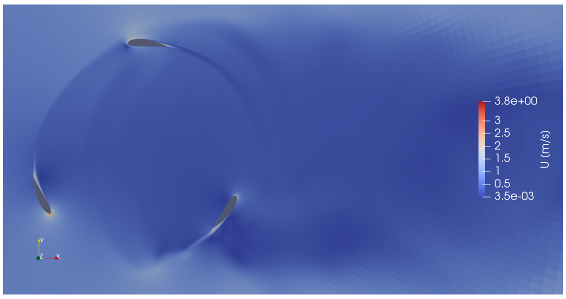

Figure 5. Velocity field in the vicinity of the turbine at the last time step at a TSR=2 and an inlet velocity=0.8 m/s

3. CONCLUSION

In order to implement a blade-embedded pitching actuator in the blade of a H-Darrieus tidal turbine it is necessary to optimise numerically the blade shape. In this paper, the methodology for such an optimisation is presented. A CFD simulation is coupled with an evolutionary algorithm to find the blade shape that presents the highest average performance during one turbine revolution. The shape of the hydrofoil is constrained by the size of the pitching actuator and its position at quarter chord. The OPAL++ software is used to govern the optimization process by generating the individual parameter sets from the variables and analyze of the results of subsequent simulations. The hydrofoil shape is retrieved by a *Python* script, which interpolates the shape with use of a B-Spline from the parameter sets. The interpolated points of the new hydrofoil are directly imported into the *blockMesh* utility for mesh generation. After creating the fully parametrised mesh the numerical simulations are executed in the OpenFOAM framework. Through this method, the optimal blade shape for a H-Darrieus tidal turbine, which should fit an actuator of 13 mm by 35 mm, can be found.

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