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Adaptive Blade Control Using Data-Driven Optimization for Ocean Current Turbines: A Hybrid Simulation Framework

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Abstract

This work builds upon a previously discussed design approach for Ocean Current Turbines (OCTs) with variable twist blades for improved energy capture and reduced loading. This methodology focuses on the intersection of two key techniques for simulating rotor behavior. Firstly, OpenFAST models are used to optimize, and secondly CFD is used for validation and detailed flow overview. OpenFAST developed by the National Renewable Energy Laboratory (NREL) is used to produce the turbine characteristics at various speed. The CFD set-up on the other hand uses an actuator line method with Large Eddy Simulation (LES) to capture the detailed wake dynamics of the flow field. These CFD simulations were using STAR-CCM+ to capture wake evolution and flow recovery trends. This paper builds upon the previous work by describing a way to model the RM1 turbine by the NREL without using any of the geometry definitions saving on mesh complexity and computational time. The actuator line method employs multiple airfoil sections that allows the authors to describe the full blade definitions of the RM1 without any of the complex geometrical bodies and allows us to later use this model in the hybrid model to change the TAD distribution in a closed loop framework. The closed loop structure is currently being used with this CFD simulation to conduct optimization for fatigue loading and power capture.
Keywords: Design optimization; Ocean Current Turbines; data-driven modelling; Computational Fluid Dynamics (CFD), Twist Angle Distribution (TAD)

Nomenclature

OCT	Ocean Current Turbines	c_t	Coefficient of thrust
LES	Large Eddy Simulations	ρ	Density
TAD	Twist Angle Distribution	A	Swept rotor Area
T_r	Rotor torque	v	*Fluid speed*
F_t	Thrust load	φ_a	Absolute twist angle
c_p	Coefficient of power		

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1. Introduction

The global demand for Energy keeps rising and hence new forms for energy sources continue to be important resources to satisfy this rise in demand. In the past few years, the interest in offshore wind and Ocean Current Turbines has increased, and hence more research and development is being conducted in these fields. This work focusses on improving the feasibility of extracting the vast amount of energy available in the ocean currents [1,2]. The work specifically attempts to improve the feasibility of the OCTs with the help of adaptive blade technology for improved energy capture, reduced fatigue loading, hence enhancing the power quality and reducing the levelized cost of energy (LCOE) [3,4,5]. The authors have developed adaptive blade design for wind applications and in this work propose adapting these blade designs for the sake of OCTs. These adaptive blades are more necessary for OCTs due to the complex and dynamic marine environment. Current OCT designs optimize over a range of operating conditions and use pitch control during operation to regulate performance, which inherently requires tradeoffs. The adaptive blades discussed would change their twist angle distribution along the blade to adapt to their changing environmental conditions, addressing the drawbacks of fixed blade designs. Ocean currents are inherently turbulent with vertical velocity gradients, and wave actions causing fluctuating loading on the blades. This causes fatigue loading and impedes grid integration and results in poor power production.

Adaptive rotors have shown advantages in various forms, Myers and Bahaj have shown optimized array layouts with adaptive rotor adjustments to improve energy capture by utilizing flow acceleration between devices [6]. Neary has conducted extensive research indicating, adaptive rotors improve energy extraction and reduce LCOE [7,8,9,10,11]. Blackmore et al. noted that adaptive rotors are better at adjusting to turbulent conditions, improving energy extraction and overall performance [12]. Nicholas-Lee et al. demonstrated the ability of bend-twist coupled blades to increase power capture by 12.5% with minimal increases in production cost [13]. In the previous work done by the authors, a method for design and control of a wind turbine blade with adaptive blades was published [14,15,16,17,18]. The active TAD control discussed in these publications indicated a 14% increase in power production and 70% decrease in loading. This paper will focus on the framework that utilizes OpenFAST and a Large Eddy Simulation conducted in starccm+ to optimize the TAD of a RM1 turbine. This work builds upon previous work by the author to design a framework to optimize the TAD for better performance characteristics including but not limited to better energy capture, reduced fatigue loading, improved wake recovery and wake steering. The methodology section will give a brief description of both the OpenFAST and LES simulation set ups and then the Results section will look at modelling results from the current and previous studies.

2. Methodology

In this section we will look at the basic nomenclature corresponding to blade design and set up the necessary background for discussing the simulation set up. The brief introduction to OpenFAST model and the machine learning framework used in previous studies will be given to familiarize the reader with the background for the hybrid modelling set up. There will also be a detailed description of the LES simulation, and the specific actuator line method carried out in this paper to simulate the RM1 turbine in normal operating conditions. This discussion will give the reader necessary background for the results discussed in the subsequent section.

2.1 Background

This study builds upon the authors previous studies that performed TAD optimization for a uniform rotor blade with OpenFAST and LES simulations. This was further improved with spanwise variable chord length and airfoil characteristics. The performance metrics seen in the previous study were rotor torque T_r, and thrust load, F_t. These are defined by equation (1) and (2).

$$T_r = 1/2 c_p \rho A v^3 \tag{1}$$
$$F_t = 1/2 c_t \rho A v^3 \tag{2}$$

Where c_p *and* c_t are power and thrust coefficients, respectively, ρ is the water density, A is swept rotor area, and v is the current wind speed. The coefficient of thrust and power are functions of blade geometry and water speed which can be seen below.

$$c_p = \mathrm{f_p}(\varphi_a, v) \tag{3}$$
$$c_t = \mathrm{f_t}(\varphi_a, v) \tag{4}$$

Where φ_a represents the TAD, described by a series of angles as measured in figure 1 defined as

$$\varphi_a(i,j) = [\varphi_a(i,j), \varphi_a(2,j), \dots, \varphi_a(n,m)] \tag{5}$$

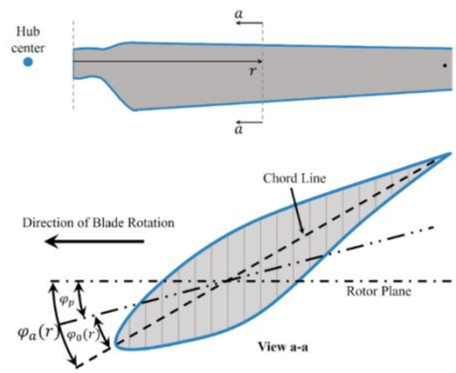

Fig. 1. Definition of the absolute twist angle, φ_a, at distance, *r,* from the blade root [19]

Variable TAD allows for the local control of the angle of attack at different radial distances, r(*i*) at fluid speeds, *v*(*j*).

2.2 Reduced Order Modelling

OpenFAST developed by the NREL is used to perform a local search of the optimization space. This allows for computational savings when it comes to the need for CFD simulations and computationally intensive operations. Reference Model 1 (RM1) with its monopile-mounted, dual-rotor configuration, provides a straightforward test platform [20]. There are no confounding factors due to the fixed foundation as it simplifies modeling due to a lack of multi-rotor interactions and platform movement. Due to these reasons the RM1 was chosen for this study. Our group has previously developed a methodology for effective generation of data driven models using machine learning and OpenFAST. The workflow pipeline for effective closed loop optimization with CFD framework and date driven methods takes the following from:

- Data Production: Generation of data points, such as with OpenFAST
- Data Treatment1: Prepare the data generated for use in the data-driven model selected. Here, this includes application of the Fast Fourier Transform (FFT).
- Model Generation: Using the prepared data as the predictors and responses for the generation of a data-driven model of choice. Here this is a Neural Network (NN).
- Optimization problem: Utilization of the generated model in the intended application.

Previous work developed a model for the frequency-domain spectral loading information for a reference system with uniform chord specifications under specific operating conditions to optimize twist profiles for fatigue damage mitigation. The simulation for this work is the RM1, subjected to a constant flow condition. The goal is to model the loading response in the rotor, specifically the frequency response, to solve an optimization problem regarding overall fatigue damage, something the frequency information is uniquely suited to do. To produce the required data, 1000 simulation iterations are run to extract the raw data to generate the data driven model. These iterations capture data from start up to steady state conditions through several flow through times at which point the data collection begins. The iterations run at identical wind conditions, and the data is collected for 50 seconds of simulation time, recording thrust loading, pitch controls, coefficient of power, coefficient of thrust. Once the data collection is completed the data was divided into training and testing data. 60% of the data was used for training data while the remaining 40% was divided equally into test data and validation data. The previous framework used GPR and NN for regression tasks for predicting state variable for applications involving the prediction of state variables. A two-layer feed forward NN was used to predict the spectral information in response to morphing.

2.3 CFD simulation

Alongside the reduced order modelling there was a need for a higher fidelity validation of the generated data. It was critical to have a CFD model run in the closed loop interface, to enable wake studies. The model used for this task was an Actuator line model in conjunction with a LES model. The LES model uses a progressively finer mesh to capture the full flow domain. the entire domain size was 240x240x500 meters and the base cell size was 10m. This was made progressively finer with cell sizes of 50%, 25%, 10%, and finally an absolute cell size of 1m at the rotor. this was done to balance between the necessary mesh resolution and computational loading. The final mesh contained ~25 million cells. The model uses the Smagorinsky sub-grid model to capture the sub-grid dynamics. The time accurate actuator line method distributes the effects of the blade onto this mesh by interpolating the blade position and using blade element method with user defined blade characteristics. This simulation assigns 9 airfoil sections to capture the changing chord characteristics of the RM1 turbine. The data for the blade profile was extracted from the OpenFAST code base that defines these blade segments. The blades also have a changing chord length also defined by the RM1 blade characteristics. The NACA airfoil definitions of these 9 blade segments and their spanwise distribution can be seen in Table 1

Table 1. Airfoil segments for RM1

Airfoil definition	Blade span
NACA6_1000	0-0.45
NACA6_0864	0.45-0.75
NACA6_0629	0.75-1.05
NACA6_0444	1.05-1.35
NACA6_0329	1.35-1.65
NACA6_0276	1.65-1.95
NACA6_0259	1.95-2.25
NACA6_0247	2.25-2.55
NACA6_0240	2.55-9.0

The chord length also varies along the length of the blade and is defined by R/r table. The baseline twist distribution is also defined as a R/r table that can then be modified between each optimization step. The turbulent inflow has a turbulence intensity of 5% and a length scale of 2m to simulate the turbulence seen in ocean currents. This CFD set up ran for 5 flow through times and the resulting flow field will be used as the initial condition for the optimization framework. Figure 2 Shows the full framework with the interactions between the CFD set up and the data driven model.

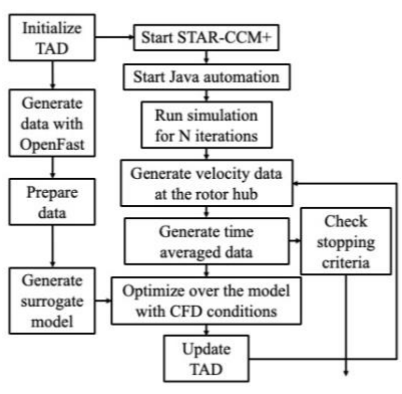

Fig. 2. hybrid modelling framework showing the interactions between the CFD and data driven model [21]

The simulation initializes with a baseline TAD and initial flow speeds of 1.04 m/s to have a rotor speed like those seen in an experimental validation of the RM1 turbine [22]. This then gets simulated in the CFD environment while simultaneously the data driven model is generating the necessary data for the optimization. Once the LES simulation returns the velocity profile along the blade the time averaged velocity profile is used to optimize with the data driven surrogate model. This iteration is carried out until a certain stopping criterion either based on optimization error or number of iterations has reached. In the following section we look at the previous studies results implementing this framework along with the modified version of the CFD simulations. The previous results show the reader the feasibility of this framework and the new CFD results demonstrate the ability to model the RM1 turbine in the LES mesh with the actuator line method

3. Results

In the following section the results from the previous study that showed load reduction for a chord data driven method and established the feasibility of this hybrid modelling approach. During this study the NN model demonstrated high prediction accuracy with an R value exceeding 0.99, this might be inflated due to a broad range of values being considered. Figure 3 a and b show the spectral prediction accuracy for both cases. To confirm the accuracy of the model, the high amplitude response was tested, and it showed model reliability in those areas. These data driven models were used, and a genetic algorithm-based Pareto optimization was conducted for various blade materials, achieving 23.09% reduction in fatigue damage. This demonstrated the workflow validation and robustness across the different materials.

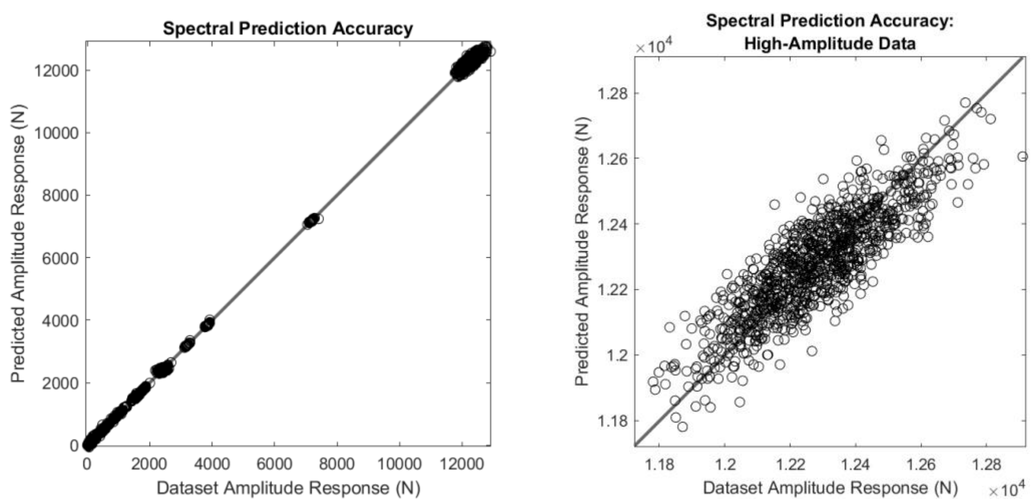

Fig. 3. NN model accuracy for training and validation data for full dataset (Left) and high amplitude data subset (Right)

CFD Results 3.1

Preliminary CFD shows that the actuator line method is successful in capturing the wake in its entirety including the tip vortices and the downstream wake as well as the root vortices. Initial analysis also shows feasibility of the framework to successfully analyze the twist distribution and varying chord length characteristics. The velocity magnitude shows mixing and momentum recovery downstream of the rotor as well as turbulent mixing. The vorticity and the lambda 2 criterion both show the nature of the vortex shedding at the tip and the critical wake mixing that need to be studied to better conduct farm level or array level control. Further these results show feasibility of modelling the RM1 turbine using the actuator line method in a LES simulation for optimization.

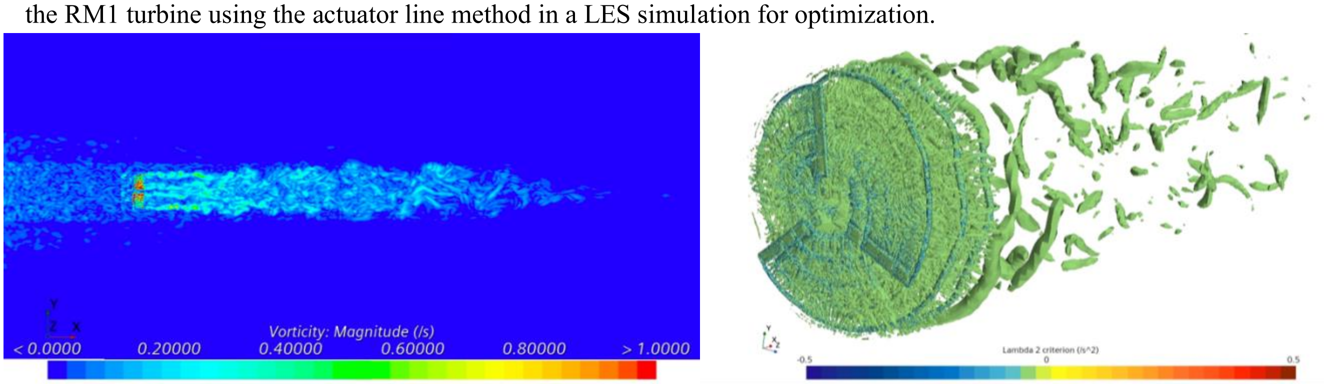

Fig. 4. Vorticity plot at the rotor plane (Left) and the Lambda 2 criterion (Right) plot showing vortex structures and tip vortices

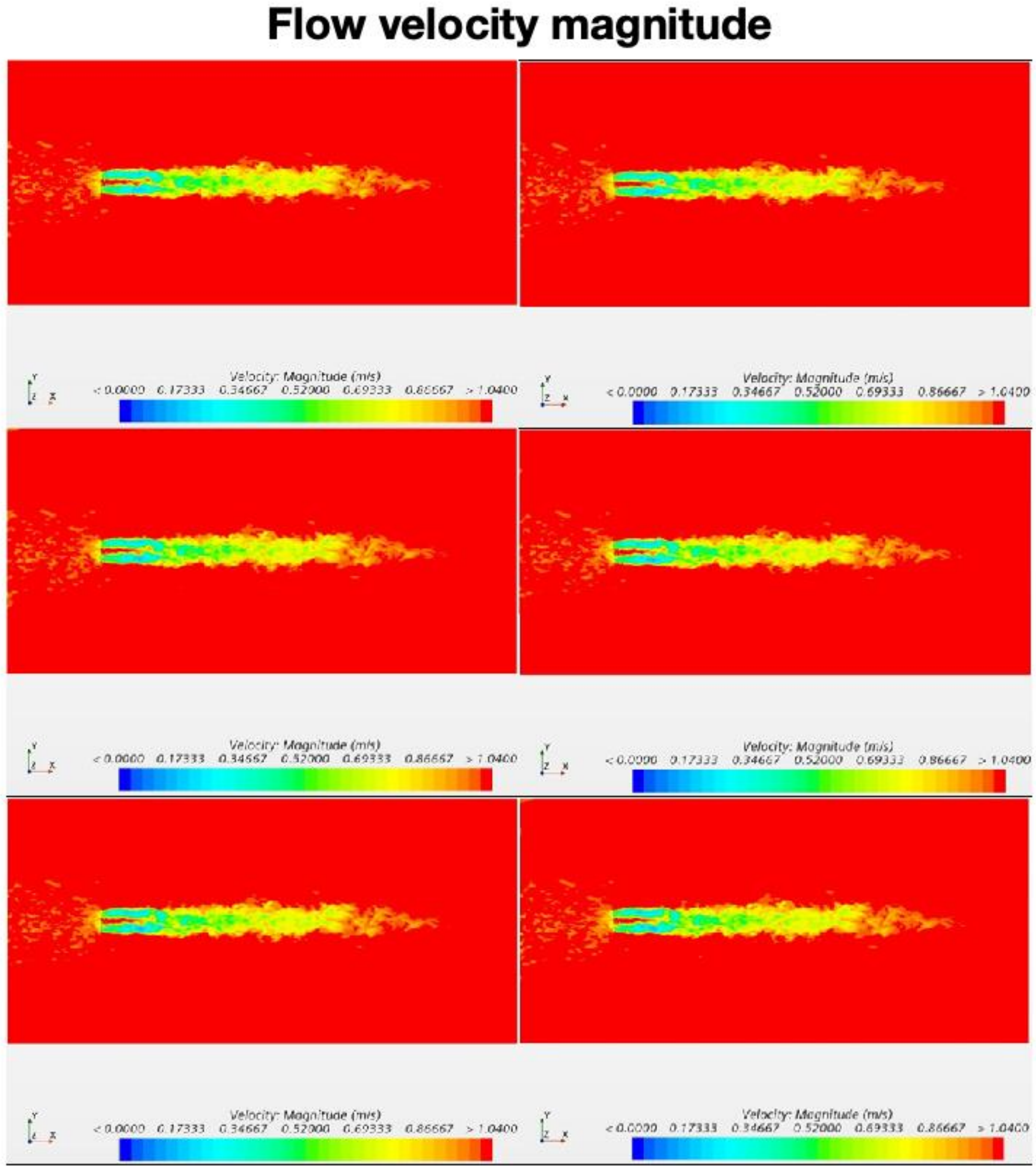

Fig. 5. Velocity cross the domain at the rotor and wake characteristics

1. Conclusion

This paper builds upon the previously discussed optimization framework published by the authors. The previous work showed an ability to do twist optimization for a uniform chord rotor using the hybrid modelling approach. This paper discussed and shared the results from modelling the RM1 turbine. The authors performed and presented the results from this the RM1 simulation with the actuator line method. They will proceed to go ahead with the optimization step to implement the framework for optimization of fatigue loading and energy extraction for the RM1 turbine. The simulation currently set up also validates the real-time interaction between the TAD search algorithm and the LES simulation. Previous work showed these frameworks to be effective at reducing the fatigue loading through a TAD search algorithm with a reduction of 23.09% for composite materials. These results are promising for showing functionality of the methodology and promises to be vital in the continued study of OCTs. More design and control optimization needs to be carried out to realize adaptive twist blades in OCTs and these types of frameworks are critical in getting to the desired technology readiness level.

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