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Araştırma Makalesi Research Article

PERFORMANCE ANALYSIS AND OPTIMIZATION OF A HELICAL CROSS-FLOW WATER TURBINE

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Keywords

Cross-Flow Water Turbine,
Performance Analysis,
Turbulence Model,
Optimization,
Comsol.

Abstract

In this study, a Computational Fluid Dynamics model is designed to investigate the performance analysis of a helical cross-flow water turbine by using Comsol Multiphysics. In order to predict the main performance characteristics of turbine such as power output and torque, a numerical model is developed which is accurate, fast and quite simple to be used for a simulation. The flow field around turbine is solved with the Rotating Machinery feature in the Comsol CFD Module using a k-ω turbulence model and a steady state formulation. The Navier-Stokes equations are used in the model which are arranged in a rotating frame in the inner domain and in fixed coordinates in the outer domain. The boundary between the inner and the outer domain is a continuity boundary condition that transfers momentum to the fluid in the inner domain. This model also uses the Frozen Rotor study type which speeds up the computation time. Then, to increase the performance of the cross-flow water turbine, a new angular velocity profile is explored with Comsol Optimization Module. Thus, a variable speed turbine control method is developed. Compared to the constant velocity control method, new angular velocity control method yielded a 3% increase in the efficiency of turbine.

HELİSEL ÇAPRAZ AKIŞLI SU TÜRBİNİNİN PERFORMANS ANALİZİ VE OPTİMİZASYONU

Anahtar Kelimeler

Çapraz Akışlı Su Türbini,
Performans Analizi,
Türbülans Modeli,
Optimizasyon,
Comsol.

Öz

Bu çalışmada, bir helisel çapraz akışlı su türbininin performans analizini, Comsol Multiphysics kullanılarak incelemek için bir Hesaplamalı Akışkanlar Dinamiği modeli tasarlanmıştır. Bir helisel çapraz akışlı su türbininin güç çıkışı ve tork gibi ana performans özelliklerini tahmin etmek için, simülasyon için kullanılması doğru, hızlı ve oldukça basit olan sayısal bir model geliştirilmiştir. Türbin etrafındaki akış alanı, bir k-ω türbülans modeli ve kararlı durum formülasyonu kullanılarak Comsol CFD Modülündeki Rotating Machinery özelliği ile çözülmüştür. Navier-Stokes denklemleri, iç alanda dönen bir çerçeve içinde ve dış alanda sabit koordinatlarda düzenlenen modelde kullanılmıştır. İç ve dış alan arasındaki sınır koşulu, momentumu iç bölgedeki akışkana aktaran bir süreklilik sınır koşuludur. Bu model ayrıca, bu çalışma için hesaplama süresini önemli ölçüde hızlandıran Frozen Rotor çalışma yöntemini kullanır. Ardından Comsol Optimizasyon Modülü ile çapraz akışlı su türbininin performansını artırmak için yeni bir açısal hız profili araştırılmıştır. Böylece değişken hızlı bir türbin kontrol yöntemi geliştirilmiştir. Bu kontrol yönteminin performansı, sabit açısal hız kontrol yöntemi altında çalışan bir türbin ile karşılaştırılmıştır. Yeni açısal hız kontrol yöntemi türbin veriminde, sabit hız kontrol metodu ile karşılaştırıldığında, %3'lük bir artış sağlamıştır.

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1. Introduction

Nowadays increasing demand for electrical energy is one of the most important issues in the world. In addition to the negative impact of greenhouse gases, the depletion of fossil fuel resources has recently increased the interest in renewable energies. Because of its huge potential, hydropower takes a particular place among these renewable energies. On the other hand, hydropower is considered as an enormous source of energy in the form of wave, tidal and marine current in the world where the water represents 70% of the earth's surface (Mehmood et al., 2012). Hydropower is derived from falling or fast running water energy, which can be harnessed for useful purposes. A lot of methods of harnessing energy from water are developed over the past decades (Khan et al., 2006). This arising kind of renewable energy which uses rivers and marine currents and shows also a good application possibility is considered as an unusual technology. The kinetic energy of water current is converted to mechanical energy in a device that rotates a generator to produce the electricity (Güney and Kaygusuz, 2010). Water resources are widely used in industry, agriculture, electricity generation as well as in people's daily lives. Since ancient times, hydropower from many water mills has been used as a renewable energy source for irrigation and operation of various mechanical devices such as grinding mills, saw mills, textile mills, tilt hammers, harbor cranes, home elevators and ore mills. As long as the power is an indispensable part of human life, the hydropower will be significant supplementary source of the power.

Hydropower offers an extensive amount of energy all over the world and exists in more than 100 countries, contributing roughly 15% of the global electricity production. In several other countries, hydropower accounts for over half of the electricity generation. Large hydropower plants are being built in Turkey that use a minor part of Turkey's hydroelectric potential. Turkey benefits from its mountainous landscape and position between three seas and it has a significant hydropower capacity estimated at approximately 433 TWh and it is thought that 140 TWh a year is thought economically viable (Sabuncu and Çolakoğlu, 2011). Hydrological data which allows projects feasibility is significant in order to efficient use of water resources. Hydrological data is presented to users by field observation, surveying and subsequent analyzes. In addition, not only the main purpose of the collected and presented data is hydrologic engineering projects but also scientific-based research plays an important role for efficient usage of water resources (Aksu and Korkmaz, 2019).

Flow is a fundamental concept of hydropower. Two main methods are used for obtaining energy from water flow. The classic method is to build a dam to constitute a static head. The other method is to extract energy from different water currents such as tides, oceans, rivers and irrigation channels (Khan et al., 2009). The river flow method extracts energy using a dam to make a head difference and then delivers water to turbines to generate electricity, while tidal flow devices extract energy directly from water streams. For generating power from tidal currents or river streams, kinetic energy has to be converted to mechanical energy by a hydropower generation device. A tidal current or river stream turbine is one of the most important and necessary part of a hydropower generation system. According to the relative position between turbine main shaft and incoming flow direction, these turbines can be classified as vertical axis turbines and horizontal axis turbines. The vertical axis turbines have the advantages of independence of flow direction, better flow direction adaptability, simple blade structure, thus low manufacture cost, low possibility of cavitation and less noise emission compared with the horizontal axis turbines (Ma et al., 2018). These vertical axis turbines are also called Axial Flow Turbines or Cross-Flow Turbines.

2. Literature Survey

The growing demand for energy due to growing population is one of the most important subjects nowadays. Beside increasing environmental effects, decreasing amount of fossil fuels make the renewable energy technologies vital to assure future energy sources and to solve environmental problems. The energy in the flows of river streams, tidal currents or other artificial water channels are considered as available source of one of the renewable energies. River Current Energy Conversion Systems (RCECS) seem convenient in harnessing energy from a stream of flowing river water to generate electricity. In order to formulate a basis for further analysis, Khan et al. (2006) discussed an extensive technology survey and comparison of various river current energy conversion systems and carried out simulations of simplified mathematical modelling of a RCECS device in Matlab. From a system engineering perspective, Khan et al. (2008) provided an overview of the technological advancements in the RCECS field and discussed various merits and prospects of this technology along with related challenges. Further Khan et al. (2009) outlined a review of the existing and upcoming hydrokinetic conversion systems and their fields of applications starting with a set of basic definitions belong to this technology. They concluded the general trends in system design, duct augmentation and placement methods based on a comprehensive survey of various hydrokinetic systems reported to date. They also presented a detailed assessment of various horizontal and vertical axis turbine systems, along with their classifications and qualitative comparisons. Güney and Kaygusuz (2010) investigated hydrokinetic energy technologies and gave some detailed information about current base of these kinds of systems. In order to familiarize with the turbine and generator used in hydrokinetic energy technology systems, some knowledge was given and the selection information of a suitable turbine has been mentioned in their work. On the other hand, Mehmood et al. (2012) presented a comprehensive review of tidal current technologies to harness energy from ocean energy sources and discussed tidal energy technologies and tidal current turbines in detail. They reported the present status of ocean energy development and also today's popular tidal current technologies. Gorlov Helical Turbine is one of the Cross-Flow Turbines and developed from the Darrieus turbine. Gorlov Helical Turbine is designed with modifying its blades by Professor Alexander M. Gorlov of North-Eastern University (Gorlov, 2004). Numerous studies about the parameters which are affecting the performance of the cross-flow water turbines have been achieved. Niblick (2012) studied experimentally and analytically the helical cross-flow turbines, where the author explored the applicability of a micro scale tidal hydrokinetic generator and emphasized on turbine design and performance. Yang et al. (2013) designed and optimized a new hydrofoil for a helical turbine placed vertically to convert the water currents to energy. Polagye et al. (2013) presented the performance characteristics of a high solidity helical cross-flow turbine rotor for a tidal current generation at the micro scale. Their results suggest that turbine rotor of micropower system can reach efficiencies as high as 25% and can easily start itself at water velocities less than 0.5 m/s. Vallet et al. (2011) aimed to offer a vision of how a generation system based on cross-flow water turbines operating in a river stream should be controlled between two operating regimes in order to maintain its continuity of service. Cavagnaro et al. (2014) performed an adaptive control method related to a helical cross-flow turbine's characteristic performance curve and rotation rate to an optimal torque set point experimentally and also in a simulation. They compared the performance of adaptive control technique to the performance of constant speed and non-adaptive control. Their results demonstrated that important improvement over constant speed operation and small improvement over non-adaptive method in simulation. Strom et al. (2017) introduced a new alternative control method which doesn't require additional moving parts for turbine. They demonstrated experimentally that this method results in a 79% increase in turbine power output compared to standard control methods. This control strategy provides a structurally powerful turbine which operates at relatively low angular velocities to succeed high efficiencies and make possible a new generation of environmentally friendly turbines for wind and water current power generation.

3. Material and Method

3.1. Mathematical Model

This section presents how to develop a numerical model for cross-flow water turbines with the use of the Rotating Machinery feature in the CFD Module of Comsol Multiphysics. Nowadays the CFD models take place increasingly in hydrodynamic researches due to the quick development of computer technology. If the CFD method is used properly, it is a powerful tool. However it is computationally expensive, particularly when it is dealing with complex geometries such as cross-flow turbines. The Rotating Machinery physics interfaces are used in models that include moving rotating parts such as in mixers, compressors, stirred tanks, turbines and pumps. The Rotating Machinery Fluid Flow interface models and solves the flow using the Navier-Stokes equations in geometries including rotating parts such as turbines. The rotation is accomplished as the inner domain is prescribed to be a rotating domain (Comsol, 2018a).

In cases where it is possible to divide the model into rotationally fixed geometries, the predefined rotating machinery multiphysics couplings can be used. The first step is to divide the model geometry into two parts that are both rotationally fixed. The second step is to specify the parts as a rotating frame or a fixed frame. Then the predefined coupling automatically performs the coordinate transformation and the joining of the fixed and rotating parts (Comsol, 2018a). The boundary between the outer and the inner domain is defined as a continuity boundary that delivers momentum to the fluid in the inner domain. The Rotating Machinery physics interface expresses the Navier-Stokes equations in a rotating coordinate system whereas the parts which are not rotated are defined in the fixed material coordinate system. The rotating and fixed domains are coupled together by an identity pair where the boundary condition is applied as a flux continuity (Comsol, 2018a).

This study explains how to model a rotating machinery simulation with the frozen rotor approach for a cross-flow water turbine. The frozen rotor approach is a computationally efficient method. This approach can deliver a decent approximation of the flow fields at a minimal computation effort. Frozen rotor means that an impeller or rotor is frozen in position and the flow in the rotating domain is considered as stationary in terms of a rotating coordinate system. The flow in each of both zones is solved using the moving reference frame equations. This approach can be described as freezing the motion of the moving part in a given position and then observing the resulting flow field with the rotor in that fixed position. The frozen rotor solution gives a general idea of the circulation pattern set up in the turbines and can produce good approximations of certain averaged flow quantities, such as the torque and power output (Comsol, 2018a).

The model presented in this study employs a Rotating Machinery, Turbulent Flow, k-ω simulation with the frozen rotor approach. Turbulence is modeled with the k-ω model instead the k-ε turbulence model. The k-ω turbulence model is a widely used model for turbomachinery simulations, with good performance for swirling flows and in the near-wall region. Although the k-ω model is better suited for these types of flows, it takes longer to converge than the k-ε model due to the strong nonlinearity in the turbulence coefficients (Comsol, 2018a).

For the improving of wind turbine blades, a great deal of airfoil types are designed in wind energy systems technology. Because of technical similarities between wind and water turbines, these airfoils can be used in water turbines. National Advisory Committee for Aeronautics (NACA) series airfoils are generally used to design the turbine blade geometry. In this study, due to its symmetrical structure, NACA 0018 airfoil profile which is very appropriate for small turbine design is used (Abbott et al., 1945). NACA four digit airfoil series specification is defined by four numbers which describe camber, position of maximum camber and thickness. The first number states the maximum camber in percentage of airfoil chord length. The second number shows the position of maximum camber in tenths of chord length. And the last two numbers express maximum thickness of airfoil in percentage of chord length. If the first two numbers of an airfoil of NACA four digit series are 00, it means that this airfoil is in symmetrical structure and has not a camber geometry (Airfoil Tools, 2020). Figure 1 shows a general NACA airfoil's profile geometry (Comsol, 2018a). In aeronautics, the chord is an imaginary straight line joining the leading edge and trailing edge of an airfoil. The chord length is the distance between the trailing edge and the point where the chord intersects the leading edge of an airfoil (Airfoil Tools, 2020).

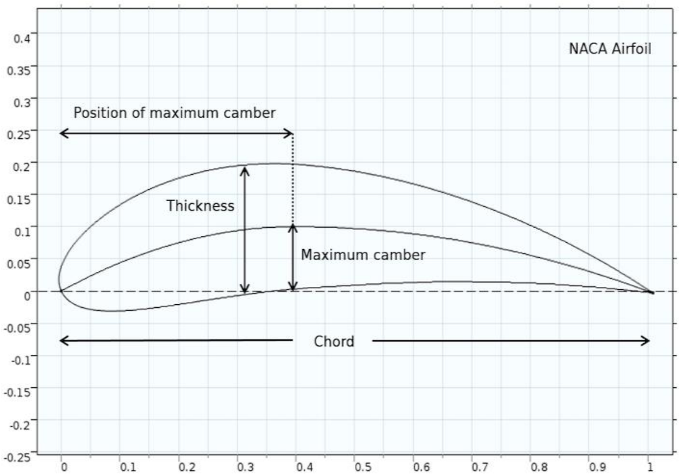

Figure 1. NACA Airfoil Profile Geometry

In this study, the numerical model is defined as a 3D CFD simulation and there are no shaft and arms in the model geometry. But there are only two circular plates at the end of turbine blades. The geometrical parameters of the cross-flow turbine design which are Radius (R), Height (H) and Chord Length (c) are given in Table 1.

Table 1. Cros-Flow Water Turbine Parameters

PARAMETER	VALUE
Profile for Turbine Blades	NACA 0018
Number of Blades	3
Turbine Radius	150 mm
Turbine Height	300 mm
Blade's Profile Chord Length	50 mm
Helical Rise Angle	60°

The coordinate system used in the numerical model of this study is shown in Figure 2. The water flows in the positive direction of the X axis. The turbine rotation and the positive direction of the Z axis comply the right hand rule. Also the initial position of the cross-flow water turbine and the definition of blade position angle (θ) are both shown in Figure 2 (Ma et al., 2018).

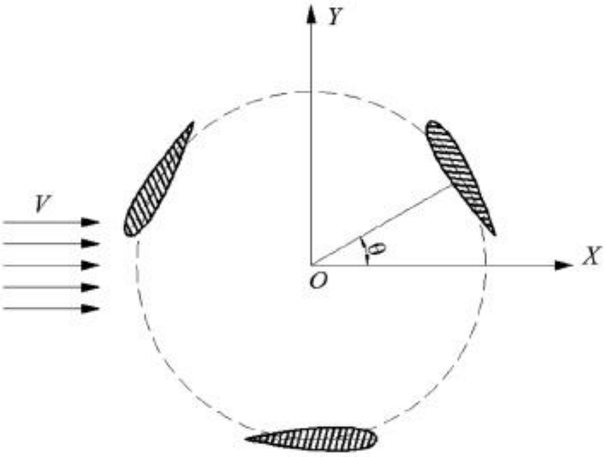

Figure 2. Coordinate System for Cross-Flow Water Turbine Model

To easily deal with the calculation results and to compare different model results, it is required to make each of performance parameters dimensionless. In this study, the dimensionless performance parameters are obtained as follows.

For any medium, the power available in the flow is defined as a measure of the kinetic energy passing per unit time and it is given by the following equation (Niblick, 2012),

$$P_f = \frac{1}{2}\rho A V^3 \tag{1}$$

where ρ is the density of the fluid, V is the free stream velocity, and A is the turbine's swept area normal to the flow. For a cross-flow turbine; A= 2RH, where R is the radius and H is the height of the turbine respectively.

The blade position of the cross-flow turbine can be defined by its azimuthal angle (θ). As the turbine blades rotate, they meet a resultant velocity which is made up of the free flow velocity (V) and the tangential velocity; V_θ=ωR, where ω is the angular velocity and R is the radius of the cross-flow turbine. For a blade at any azimuthal position, the resultant velocity is expressed by the following V_R equation (Niblick, 2012),

$$V_R = \sqrt{(V + V_\theta cos\theta)^2 + (V_\theta sin\theta)^2} \tag{2}$$

A common set of dimensionless performance parameters are usually used for wind and hydrokinetic turbines. The tip speed ratio (TSR) represents the rotational speed of the turbine and it is described by the rate of rotation speed of the turbine blade at the blade tip relative to the free stream velocity. Then the tip speed ratio is defined as the ratio of the tangential velocity to the free stream velocity with using the below-given formulation (Ma et al., 2018),

$$TSR = \frac{\omega R}{V} \tag{3}$$

where ω is the angular speed of the turbine and R is the turbine radius.

The angle of attack (α) can also be defined. The angle of attack is a measure of the angular distance between the resultant velocity and the chord line of the blade. The angle of attack is calculated by the following equation (Niblick, 2012),

$$\alpha = tan^{-1}\left(\frac{sin\theta}{TSR + cos\theta}\right) \tag{4}$$

The pressure differences and shear stresses along the blade wall cause the lift (L) and drag (D) forces on the hydrofoil of the blade. And the drag force is defined by the component in line with the relative velocity vector and the lift force is defined by the component in the perpendicular direction. These drag and lift forces on the blades together produce a torque about the cross-flow water turbine axis. This torque is made of the tangential components of the lift and drag forces on the blades multiplied by the turbine radius and it is given by the following expression (Ma et al., 2018),

$$T = R(Lsin\alpha - Dcos\alpha) \tag{5}$$

The coefficient of the torque (C_T) is calculated as the ratio of the torque produced by the turbine to the torque produced by the free stream flow if all of the kinetic force can be accumulated at the full radius. The coefficient of torque can also effectively describe the torque for a three dimensional blade and it is defined as the following equation (Niblick, 2012),

$$C_T = \frac{T}{\frac{1}{2}\rho V^2 AR} \tag{6}$$

The power received by the turbine is formulated as the following expression (Polagye et al., 2013),

$$P = T\omega \tag{7}$$

The power performance coefficient of a turbine (C_P) which is also called efficiency, is defined as the ratio of the shaft power output to the kinetic power output on a cross-sectional area at the same size as the turbine. The power coefficient of a turbine (C_P) is a measure of the efficiency of this power received from the total power available. And its relationship with the coefficient of torque (C_T) is given by the following equation (Ma et al., 2018),

$$C_P = \frac{P}{P_f} = \frac{T\omega}{\frac{1}{2}\rho A V^3} = TSR.C_T \tag{8}$$

According to Equations (5) and (4) with Figure 2; the torque is the function of θ and the total torque value in one period is obtained by the integration of the torque function along the rotor blade surface by the following equation (Ma et al., 2018),

$$T = \frac{N}{2\pi}\int_0^{2\pi} T(\theta)d\theta \tag{9}$$

where N is the number of blades. In Comsol Multiphysics, the integration operator "*intop*" is applied to the surface of the rotor blades, which is defined at the Definition section in Comsol. Furthermore, the notation "*spf*" is referred to the Rotating Machinery of CFD module and "*stressx*" and "*stressy*" are stresses in X and Y coordinate directions in Comsol Multiphysics. With the use of a numerical model, a torque value can be obtained easily.

Generally, lift and drag forces are defined as the forces acting on objects that are perpendicular and parallel to the flow direction, respectively. These forces are created due to the pressure and viscous forces acting on the surface of the hydrofoils. Based on the obtained total stress vector on the surface of the hydrofoils, drag and lift forces are obtained by integrating the total stress components along the surface of the hydrofoils. To exam the contribution of pressure and viscous flow to drag and lift forces, they can also be calculated separately. Integrating the total stress components "*spf.T_stressx*" and "*spf.T_stressy*" along the surface of the hydrofoils in Comsol Multiphysics, the drag force along the horizontal direction and the lift force along the vertical direction can be calculated (Ma et al., 2016).

In this study, the helical cross-flow water turbine, also known as the Gorlov turbine, with three blades is investigated. The dimensions of the turbine such as Height; H=0.30 m and Radius; R=0.15 m are chosen as shown in Table 1, because they are convenient for a small scale cross-flow water turbine. The NACA 0018 hydrofoil profile coordinates required for the three dimensional blade drawing are taken from Airfoil Coordinates Database which contains approximately 1600 aircraft airfoil coordinates (Airfoil Tools, 2020).

In the first step, hydrofoil profile is drawn in Comsol Multiphysics using the NACA 0018 hydrofoil profile coordinates. Figure 3 shows the NACA 0018 hydrofoil profile drawing in design software. NACA0018 hydrofoil has maximum thickness 18% at 30% chord length and maximum camber 0% at 0% chord length (Abbott et al., 1945). In this study, the chord length (c) is chosen as 0.05 m as shown in Table 1.

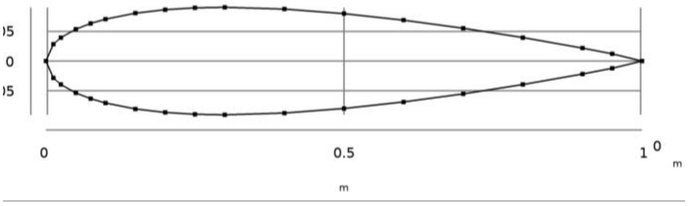

Figure 3. Blade Hydrofoil Drawing

Then the turbine blades are drawn with the helical curve at Height (H) and Radius (R) which coordinates are calculated by the following geometric correlation formulas (Gorlov, 1998)

$$\begin{aligned} x &= R\cos\varphi \\ y &= R\sin\varphi \\ z &= R\,\varphi\tan\delta \end{aligned} \qquad (10)$$

where φ is the helical rotation angle and δ is the helical rise angle. Using these geometric correlation formulas in Microsoft Excel or LibreOffice Calc, we can multiply the coordinates of the helical curve of the hydrofoil profile to form the three-dimensional turbine blade drawing. By using these coordinates, the helical curve can be plot in Comsol. This plotting process is shown in Figure 4.

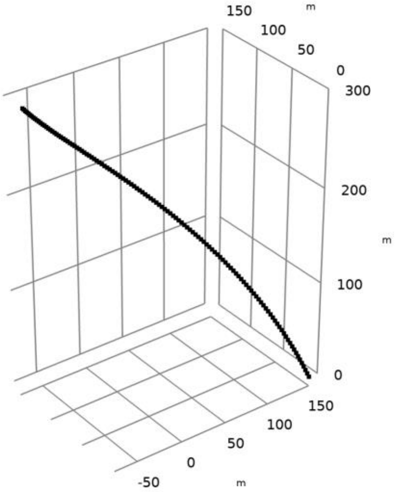

Figure 4. Blade Helix Curve Drawing

Two solid bottom and upper cylindrical blade connection elements are drawn and our solid model is completed (Özekes, 2019). Figure 5 shows the final version of the cross-flow water turbine design.

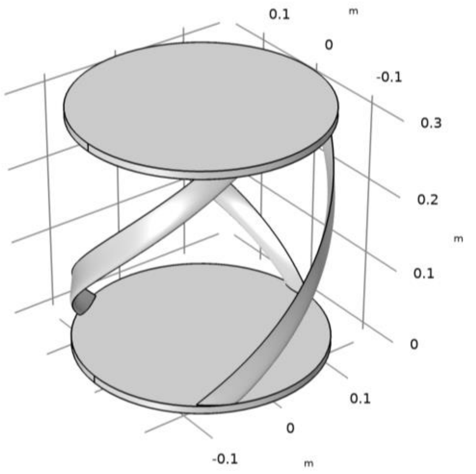

Figure 5. Design of Cross-Flow Water Turbine

The length of the control volume along the free-stream direction is equal to 32R, while its width in the Y and Z direction is 12R as shown in Figure 6. The fluid in the control volume is chosen as water in Comsol.

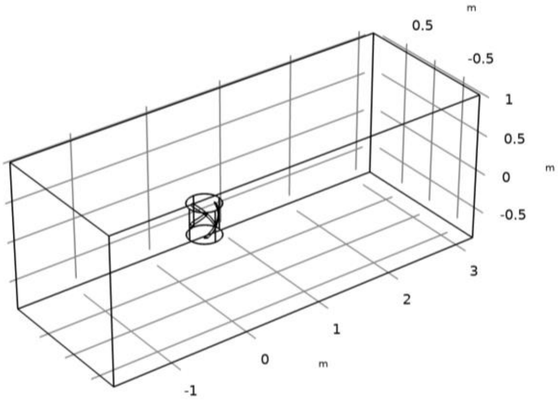

Figure 6. Control Volume of Cross-Flow Water Turbine Model

The lateral, upper and lower walls of the control volume and the surface of the turbine blades are determined as the wall boundary condition. At the same time, the left and right walls of the control volume are set as the inlet and outlet where the water flows evenly along the horizontal direction. At the control volume's fixed walls, no slip boundary conditions are applied. The boundary condition on the rotating turbine blades are set to rotate with the same velocity as the counter clockwise rotation condition. The boundary condition is defined as a velocity on the inlet surface; the inflow velocity is only directed along the X axis and equals V m/s. The outlet surface is set as a pressure outlet.

Before performing a simulation analysis, the model geometry is divided into nodes and elements in the meshing process. The mesh is configured to be tightest around the turbine blades, in order to resolve the flow in the inner domain of the model. In this study, mesh independency is conducted to assure that the number of the mesh is adequate for estimating the maximum velocity around blades for water flow velocity V = 0.8 m/s and TSR=1.5. Five different numbers of the mesh is generated for the model as shown in Figure 7. The number of domain elements is varied from 170.2 thousands to 5.2 millions.

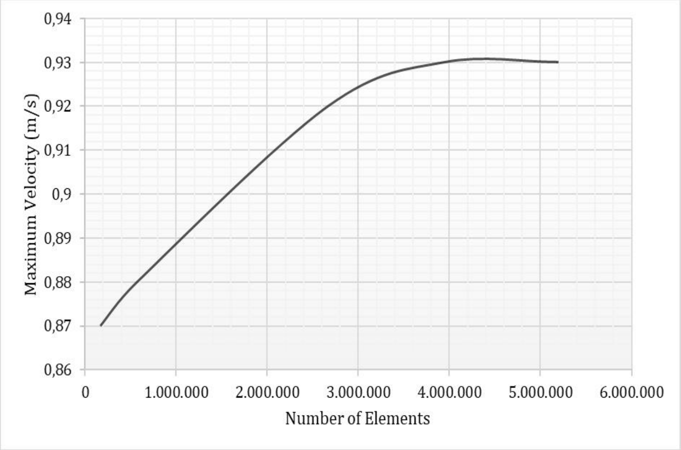

Figure 7. Mesh Independency of Cross-Flow Water Turbine Model

Thus, the final model meshing is shown in Figure 8. The mesh used to discretize the fluid domain and the turbine blade is characterized by tetrahedral elements. The maximum element size for the entire domain is set to 0.0837 m, whereas the minimum element size is 0.01302 m. Because the mesh is configured to be tightest around the blades, the high concentrated mesh distribution is applied close to the blades surface. The maximum element size for the blades surface is set to 0.03536 m, whereas the minimum element size is 0.0018228 m.

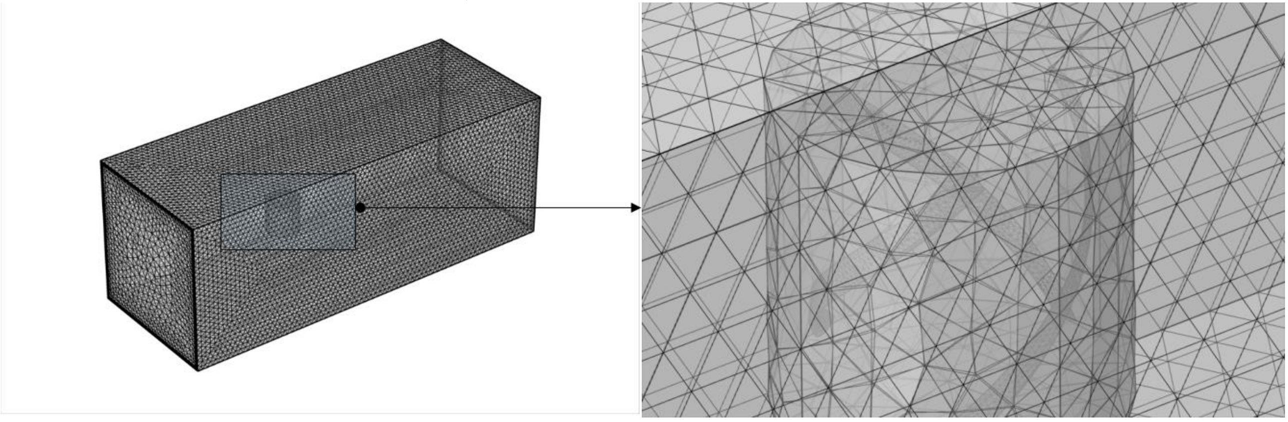

Figure 8. Meshing of Control Volume (left) and Cross-Flow Turbine Model (right)

Then the frozen rotor solution is performed. Figure 9 shows the fluid velocity magnitude around the blades of the turbine for inlet velocity V=0.8 m/s and TSR=1.5. The maximum velocity is about 0.93 m/s.

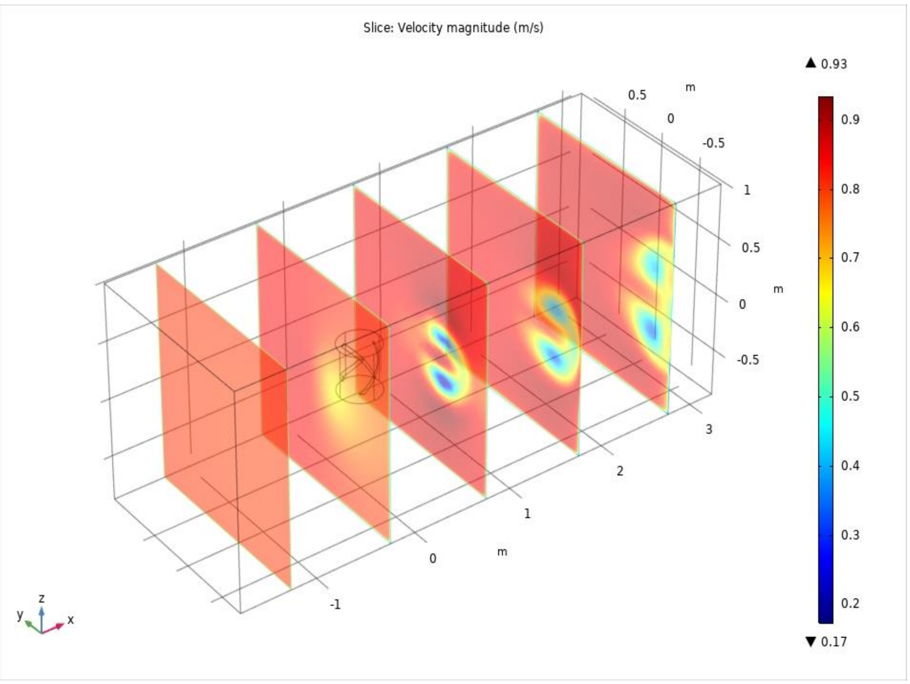

Figure 9. Velocity Magnitude Around Blades of Cross-Flow Water Turbine

Figure 10 presents fluid pressure around blades due to the surrounding water flow for inlet velocity V=0.8 m/s and TSR=1.5.

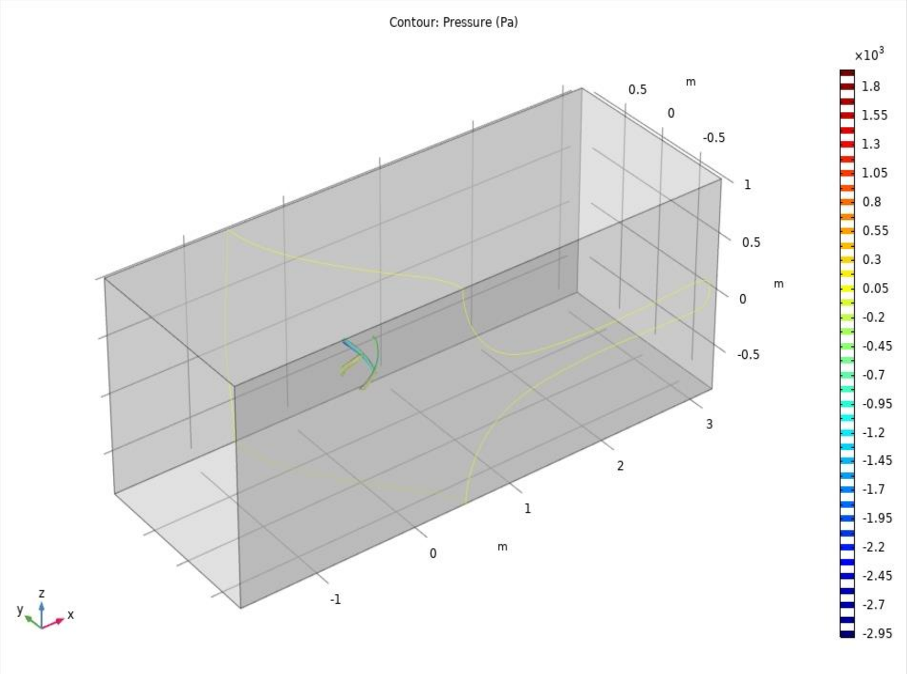

Figure 10. Fluid Pressure Around Blades of Cross-Flow Water Turbine

At last the performance parameters of the cross-flow water turbine can be calculated with Equations (6), (7), (8) and (9) which are given as above.

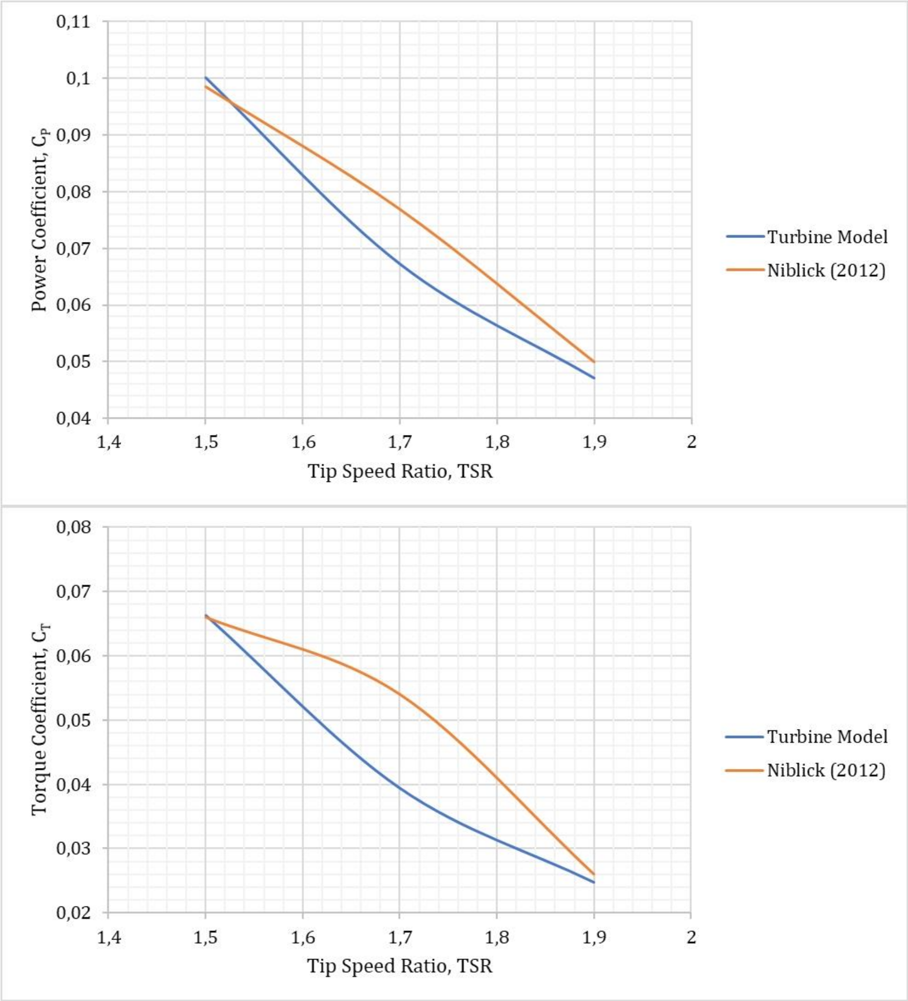

Figure 11. Comparison of C_P and C_T predictions of Presented Model and Experimental Results from Niblick (2012)

3.2. Validation of Turbine Model

In order to validate the numerical turbine model, a vertical axis three-bladed helical cross-flow water turbine is simulated with the same geometrical dimensions and flow conditions as in the experiments of Niblick (2012) at a single flow speed, V=0.8 m/s. The model results illustrate that the simulations agree well with the experimental results as shown in Figure 11. The simulations overestimate the torque coefficient (C_T) by about a difference of 0.0003 at TSR=1.5, while it is underestimated about a difference of 0.0146 at TSR=1.7 and about a difference of 0.0012 at TSR=1.9. The simulations overestimate the power coefficient (C_P) by about a difference of 0.0017 at TSR=1.5, while it is underestimated about a difference of 0.0096 at TSR=1.7 and about a difference of 0.0028 at TSR=1.9. The model presented in this study can be used in numerical analyses of any helical cross-flow water turbines which have similar configurations in different water flow conditions as long as the model meshing remains reasonably fine.

4. Optimization of Turbine Control Method

4.1. Optimization

In order to improve a design so that it minimizes energy consumption or maximizes the output in an engineering problem, the Comsol Multiphysics Optimization Module general interface is used to compute optimal solutions. In an optimization process, any engineering model inputs such as geometric dimensions and part shapes or material properties and material distribution can be used as design variables, and any model output can be used as objective function. The optimization process generally finds the best performance values of control variables or design variables of a model which are quantified by means of an objective function (Comsol, 2018b).

For Comsol Multiphysics optimization, the forward model containing the geometry and the physics is composed in the first step. Then the parameters in the Global Definitions are defined, or the control variables to an

Optimization interface are added. The forward model solves properly for some reasonable values of the control variables before proceeding with defining the objective function and constraints, and then finally the optimization problem is solved (Comsol, 2018b). After a Comsol Multiphysics model which include a physical design have been solved, an objective function is commonly attributed to it as a figure of merit. This objective function can quantify all the performance parameters of the system. This objective function changes when some parameters or control variables are varied. These parameters or variables can control any part of the design such as dimensions, boundary conditions, loads, material distribution, material properties and so forth. The control variables often have a set of bounds and design constraints associated with them. For example, dimensions must be within some limits, geometric features must not come to close to each other, only certain materials are possible, and so on.

When optimizing a system modelled as a Multiphysics model, there may also be performance constraints present, which depend on the model solution. In general, an optimization problem is when you want to improve the objective function by varying the control variables within some set of constraints (Comsol, 2018b). In this study, the objective function is chosen as C_P equation which is given by Equation (8) above. Then the optimization problem becomes the maximization of C_P. The control variable is chosen as the angular speed of the turbine (ω) with lower bound of 10 rpm and upper bound of 100 rpm. The optimization problem formulation is given as below (Comsol, 2018b),

$$\begin{gathered}\max_{\omega}\{C_P(\omega)\}\\ 10rpm \leq \omega \leq 100rpm\end{gathered} \tag{11}$$

4.2. Turbine Control Methods

For a modelled system, optimizing process of the system performance for effective control and operation requires critical attention. While the cross-flow turbine is in the running mode, the control objective is to maximize the energy received from water flow (Khan et al., 2008). As shown in Figure 12, the tests made in the field for Water Flow Velocity = 0.8 m/s, point out that maximum C_P appears over a narrow range of TSR which changes with V (Niblick, 2012). The power coefficient of a turbine sharply decreases for small disturbances around optimal TSR. This situation requires a control algorithm to operate the cross-flow water turbine at or near optimal condition in order to supply the need of generation requirements. This control algorithms also can help to reduce turbine structural loads and provide the improvement of the turbine survivability (Polagye et al., 2013).

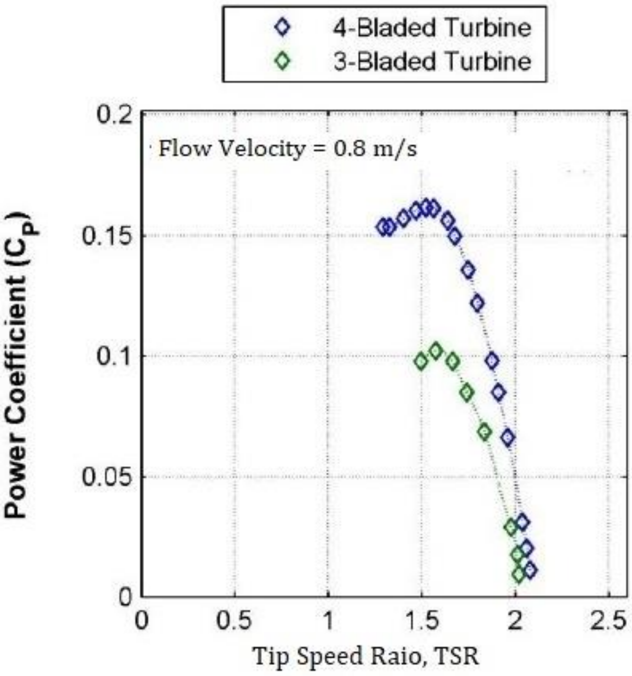

Figure 12. The Power Coefficient C_P Predictions of Experimental Results from Niblick (2012)

Because of technical similarities between wind and water turbines, wind turbine control strategies can be used in water turbines (Cavagnaro et al., 2014). Now with the developments made so far, adequate technical information is available in the wind energy engineering systems. The stall and pitch control which are two general control methods used in wind turbines, can be investigated to understand the effectiveness of a water turbine system control (Khan et al., 2008). As mechanically varying blade pitch control is an applicable method for horizontal axis or straight bladed cross-flow turbines, helical cross-flow turbines can be controlled by changing the certain load on the generator to adjust either rotor torque or rotational rate. Maximum Power Point Tracking (MPPT) control methods, well known in wind turbine applications and under research for water turbines, rely on a well defined performance curve and allows the controller to track the maximum power point as a function of rotation rate or power output (Polagye et al., 2013). Thus common control approaches of cross-flow water turbines involve the strategy of MPPT which is a feedback control method and it is targeting operation at a single optimal point based on a turbine’s typical performance curve while benefiting measurements of rotation rate, power generation and inflow velocity (Cavagnaro et al., 2014). When the generator coupled the turbine is in a grid-connected operation, the system must provide the levels of active and reactive power demanded by the grid. If it is operating in stand-alone mode, the system must provide the demanded power by the load and supply the requested output voltage amplitude and frequency. Because the cross-flow turbine systems benefit from a continuous and relatively slow variable resource, they are suitable for assuring this method. The rotational speed control in MPPT is preferred to the torque control because it can assure steady operation of cross-flow turbines at a low speed which is advised for reasons related to the mechanical structure and the over speed regime which must be avoided (Vallet et al., 2011).

5. Result and Discussion

In this study, the turbine rotation rate as a function of blade position is optimized and it is demonstrated that this approach results in a 3% increase in the power output compared to industry standard control methods. The turbine rotation rate as a function of azimuthal blade position method is applied without improving the mechanical complexity of the cross-flow turbine (Strom et al., 2017). In this study, a new angular velocity profile is explored to increase the performance of the cross-flow water turbine. Then the performance of this control method is compared to a turbine operating under the standard control method of constant angular velocity control as shown in Figure 13. The new angular velocity control method produced a little increase in the turbine efficiency. Compared to the constant velocity control case, the new angular velocity control method yielded a 3% increase in the efficiency for water inlet velocity V=0.8 m/s.

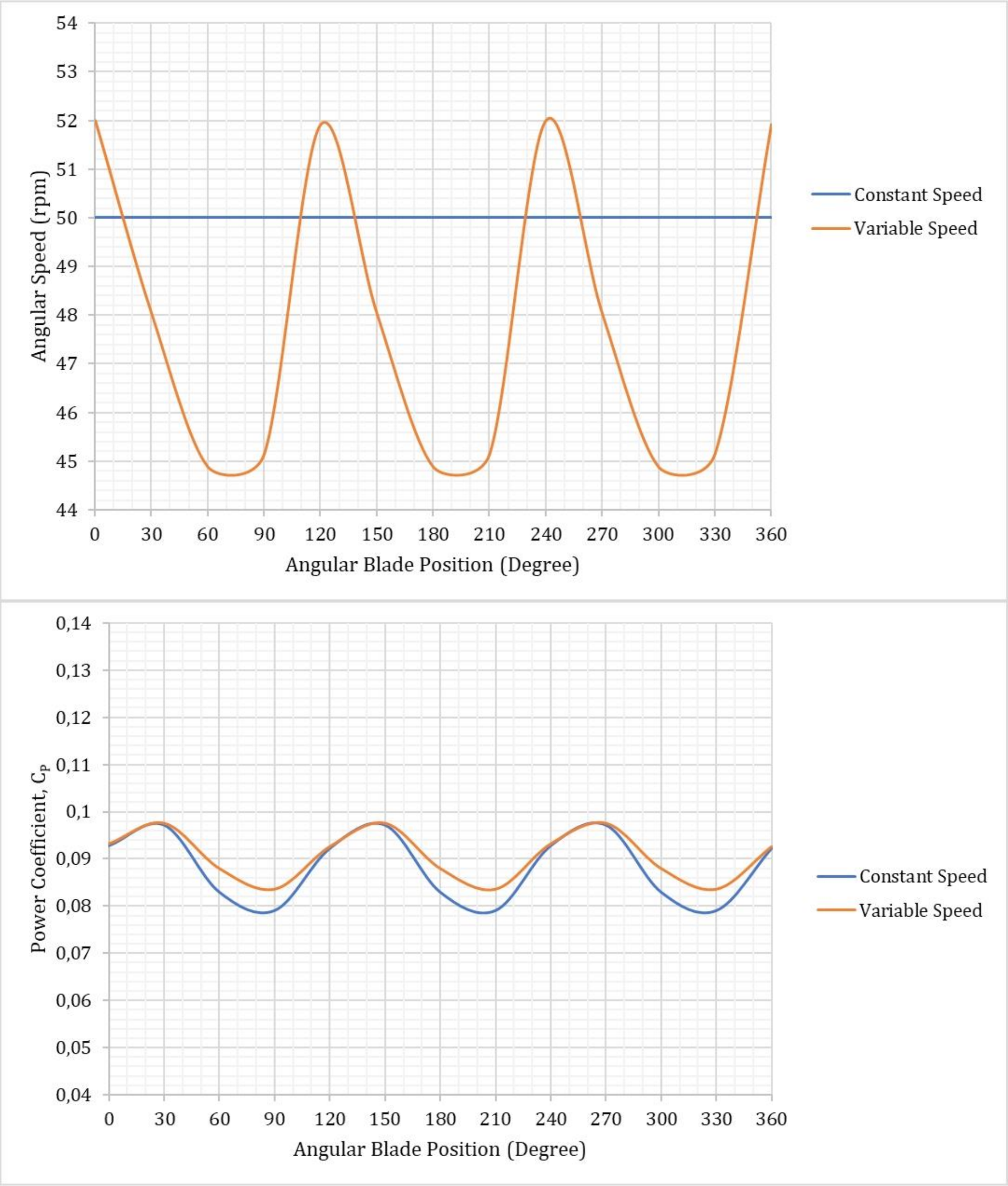

Figure 13. Comparison of C_P Predictions of Constant and Variable Speed Control Results

The model developed in this study can be used to calculate the main performance characteristics of a cross-flow turbine such as the coefficient of torque and the power performance coefficient of the turbine under different loading conditions. The model can also be used to decide and to optimize the control method of the turbine for different water flow velocities. In the future works, the cross-flow turbine design parameters such as turbine height and diameter, blade chord length, and number of blades can be changed and this model can be used easily.

Nomenclature

A = turbine's swept area
c = turbine blade's profile chord length
C_T = torque coefficient
C_P = power coefficient
D = drag force
H = turbine height
N = number of blades
L = lift force

P = power
P_f = power available in flow
R = turbine radius
T = torque
V = flow velocity
V_R = resultant velocity
V_θ = tangential velocity
x = coordinate along X axes
y = coordinate along Y axes
z = coordinate along Z axes
θ = blade position angle
α = angle of attack
ρ = density of fluid
ω = angular velocity
φ = helical rotation angle
δ = helical rise angle
CFD = computational fluid dynamics
MPPT = maximum power point tracking
NACA = national advisory committee for aeronautics
RCECS = river current energy conversion systems
TSR = tip speed ratio

Conflict of Interest

No conflict of interest was declared by the author.

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