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MODELLING THE HYDROKINETIC TURBINE

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Abstract: Hydrokinetic turbines are an emerging type of hydroenergy converters used for small rivers and streams usually in run-of-the-river installations. Run-of-the-river installations are micro-hydropower plants built without significantly altering the natural flow of the river (no dams, no reservoir). They represents one of the most environment friendly hydropower plants available today. In order for these turbines to be deemed a cost effective solution, extensive research is required. To this end, a mathematical model of the hydrokinetic turbine is required. The aim of this paper is to determine a model of a hydrokinetic turbine using polynomial regression. A model is necessary for simulating the energy conversion system which is, in turn, necessary for designing the control of the system, the protection, etc. The power coefficient on which the model is based describes the efficiency of the turbine in extracting power from the water. It is highly dependent on the characteristics of the turbine: its type, shape, dimensions, material, etc. However, the power coefficient is seldom provided by literature. Therefore, being able to obtain an estimative relationship based on experimental data is a necessity. Since hydrokinetic turbines have a very different, less controllable installation compared cu conventional hydropower plants (zero head with no reservoir), they are modelled in a completely different fashion.
Keywords: regression, hydrokinetic turbine, power coefficient

INTRODUCTION

The current global energy crisis has forced researchers to find new and innovative ways of generating energy, pushing the boundaries of science and technology. The main challenge is not only extracting more energy, but doing it in a more environmentally friendly way. This is a serious problem for large power plants, which can potentially generate more power, but at the cost of a very high carbon footprint. One solution could be the use of small-scale renewable energy sources, such as micro-hydropower plants. These small sized installations, generating between 5 and 100 kW, which can be installed to power remote areas or standalone loads, harnessing energy from nearby rivers or streams. Compared to other renewable energy sources, micro-hydropower plants have certain advantages such as higher efficiency and slower change rates. One such hydropower source is the hydrokinetic turbine [1,2].

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Their advantages compared to conventional hydropower plants are lower costs, scalability, simpler mechanical structure and the ability to generate energy near the place of consumption as well as a much smaller effect on the ecosystem. Their disadvantages are the frequent presence of floating and submerged debris, reduced adaptability to consumer variations and possible damaging during flash floods [1,3].

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WATER TURBINE MODELING

Since hydrokinetic turbines have a very different, less controllable installation compared cu conventional hydropower plants (zero head with no reservoir), they are modelled in a completely different fashion [4]. Given that their structure and functioning are similar to those of wind turbines, they are modelled based on the same principles. Wind turbines utilize the power of the wind, transforming it into rotational power. This is then changed into electrical power with the help of a generator and, usually, a gearbox. Electrical power is used to supply a load, but there may be other components between the generator and the load that ensure that its particular requirements (voltage level, frequency, etc.) are being met [5]. The models of the individual components of the system as well as the model for the interaction between the components are determined based on the transformation of the power. Therefore the bare minimum models required to simulate a wind turbine system are [6]:

- the aerodynamic model which represents the transformation from wind power to rotational power and pertains to the turbine itself;

- the mechanical model which represents the interaction between the turbine and the generator with/without a gearbox;
- and the generator model which represents the transformation from rotational power to electrical power and pertains to the generator.

In this paper, the authors are only concerned with modeling the turbine, hence the only model discussed here will be the aerodynamic model which, considering the fact that the turbine is a water turbine, will be called the hydrodynamic model. The aim of this paper is to provide a relatively low complexity hydrodynamic model for a constant-pitch hydrokinetic turbine.

THE HYDRODYNAMIC MODEL

Hydropower depends on the speed and flow rate of the water flowing through the turbine. The theoretical maximum power available from such a turbine is equal to the kinetic energy ($^1/_2\,mv^2$) of the water passing through the turbine, which can be expressed as [1, 7]:

$$P_h=0.5\rho Qv^2 \quad (1)$$

where: ρ is the density of water and v is the speed of water. Q is the flow rate of water, being described by the following relationship [1, 7]:

$$Q = Av \quad (2)$$

where A is the cross-sectional area of the turbine.

The hydraulic power can be derived from relationships 1 and 2 as:

$$P_h=0.5\rho Av^3 \quad (3)$$

The power that can be extracted by a hydrokinetic turbine depends on the efficiency of the turbine, as described by its power coefficient C_P [8, 9]. C_P is defined as the ratio of the actual power delivered by the turbine (P_{ht}) to the theoretically available power of the water (P_h) [1,7]:

$$C_p=\frac{P_{ht}}{P_h} \quad (4)$$

Based on relationships (3, 4), the output power of the turbine can be expressed as:

$$P_{ht}=0.5C_p\rho Av^3 \quad (5)$$

Since the river speed varies slowly over time, the most commonly used hydrokinetic turbines are fixed-pitch: $C_P(\lambda)$, where λ is the speed ratio defined as [1, 7]:

$$\lambda=\omega_r R/v \quad (6)$$

where ω_r is the rotational speed.

THE POWER COEFFICIENT C_P

Relationships for $C_P(\lambda)$ are seldom found in literature and the given ones [4, 5, 7] are highly dependent on the type of turbine used (Figure 1), as well as its shape, dimensions, material, etc. One solution is to find the relationship using data from an existing turbine through polynomial regression. This method will lead to finding a polynomial function $\mathbf{C_{Px}(\lambda)}$, where x is the order of the polynomial, using a set of discrete experimentally determined values. This method is demonstrated using data provided by [1].

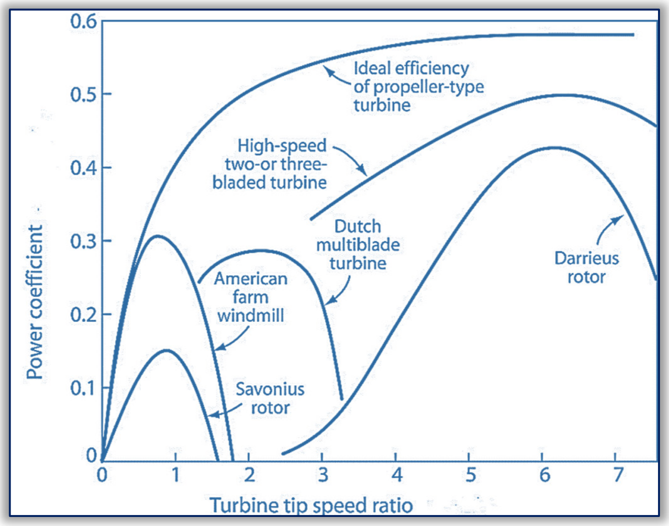

Figure 1. Power coefficient for different types of turbines [10]

Multiple polynomial expressions with orders between 5 and 10 have been thus obtained. Relationships of lower orders were not given due to low precision. These relationships can all be used to simulate the turbine depending on the accuracy required by the simulation. In order to find the best fit for the data given, the values of the standard deviation and the Pearson correlation coefficient for each expression must be taken into consideration. These quality indicators, along with the coefficients of the polynomial expressions are given in Table 1.

The most accurate approximation (minimal standard deviation and a correlation coefficient very close to one) is that obtained by a polynomial expression of the tenth order of the form:

$$C_{P10}(\lambda)=c_{10}\lambda^{10}+c_9\lambda^9+c_8\lambda^8+c_7\lambda^7+c_6\lambda^6+c_5\lambda^5+c_4\lambda^4+c_3\lambda^3+c_2\lambda^2+c_1\lambda+c_0 \quad (7)$$

The graphical representation of the variation of the power coefficient C_p based on the experimental data, as well as of the estimated power coefficient C_{P10} according to the tip-speed-ratio λ are shown in Figure 2.

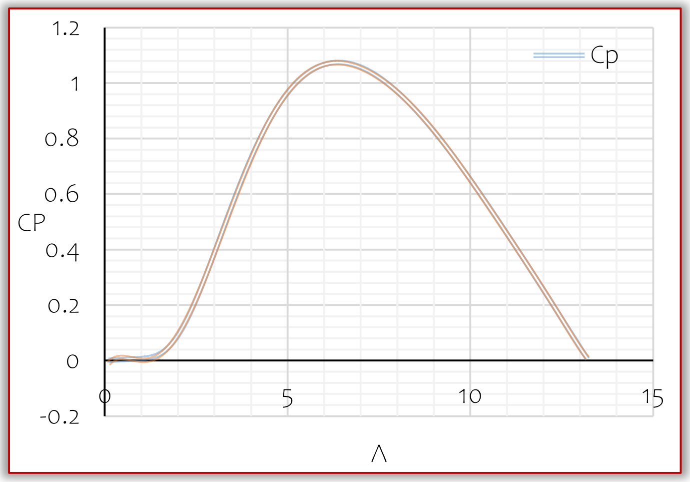

Figure 2. Experimental data and tenth order polynomial regression C_{P10} as a function of λ

Table 1. The values of the coefficients and of the quality indicators

Order	Coefficients	Quality indicators
5	c_5=-8.54215 $\cdot 10^{-5}$, c_4=0.00349077, c_3=-0.051324348, c_2=0.296784331, c_1=-0.420405312, c_0=0.127342352	RMSE: 0.162156199 Correlation coefficient: 0.998637
6	c_6=-2.52329 $\cdot 10^{-6}$, c_5=1.52576 $\cdot 10^{-5}$, c_4=0.001966774, c_3=-0.040467936, c_2=0.260337255, c_1=-0.370811775, c_0=0.11044871.	RMSE: 0.158873265 Correlation coefficient: 0.998691666
7	c_7=3.04083 $\cdot 10^{-6}$, c_6=-0.000144074, c_5=0.002625396, c_4=-0.022223132, c_3=0.077351441, c_2=-0.025770853, c_1=-0.079832401, c_0=0.034260413	RMSE: 0.092381068 Correlation coefficient: 0.999557824
8	c_8=-6.07676 $\cdot 10^{-7}$, c_7=3.53692 $\cdot 10^{-5}$, c_6=-0.000847159, c_5=0.010663518, c_4=-0.073908635, c_3=0.262562848, c_2=-0.368330677, c_1=0.191720015, c_0=-0.022581018	RMSE: 0.03559426 Correlation coefficient: 0.999934369
9	c_9=4.77701 $\cdot 10^{-8}$, c_8=-3.46672 $\cdot 10^{-6}$, c_7=0.000107019, c_6=-0.001822371, c_5=0.018481979, c_4=-0.111348347, c_3=0.366152862, c_2=-0.519797748, c_1=0.288354707, c_0=-0.039258557	RMSE: 0.02790428 Correlation coefficient: 0.999959665
10	c_{10}=8.45877 $\cdot 10^{-9}$, c_9=-5.14738 $\cdot 10^{-7}$, c_8=1.24952 $\cdot 10^{-5}$, c_7=-0.000145141, c_6=0.000603993, c_5=0.003862527, c_4=-0.05674158, c_3=0.245383463, c_2=-0.376175568, c_1=0.212710609, c_0=-0.028223172	RMSE: 0.024747898 Correlation coefficient: 0.999968274

CONCLUSIONS

This paper provides a simple yet accurate method of determining the model of a hydrokinetic turbine. The model can be used to simulate the turbine as well as to improve its features. It can also be used to design the energy conversion system centered on the turbine to ensure compatibility between the components. It can also be used to design the control system that ensures the maximization of the power obtained from the water by the turbine.

The functions obtained in this paper are polynomial functions, but other types of functions such as power, exponential, moving average, or even custom functions can be used according to the level of complexity/simplicity and performance required.

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