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Implementation of regression models to estimate the power coefficient in a turbine H-Darrieus

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Abstract: This research study examines the efficacy of various regression models in estimating the power coefficient derived from the alteration of solidity and TSR in a hydrokinetic turbine of the H-Darrieus type. The objective is to identify the optimal model that accurately represents the turbine's behavior, thereby determining the optimal operating point and developing a predictive equation for the model, which would facilitate understanding of the turbine's behavior without the need for numerous simulations. The optimal model was identified as the one who include the linear, quadratic and the combinate effects as an equation of four order.

Keywords: H-Darrieus, Regression Models, ANOVA, CFD.

Introduction

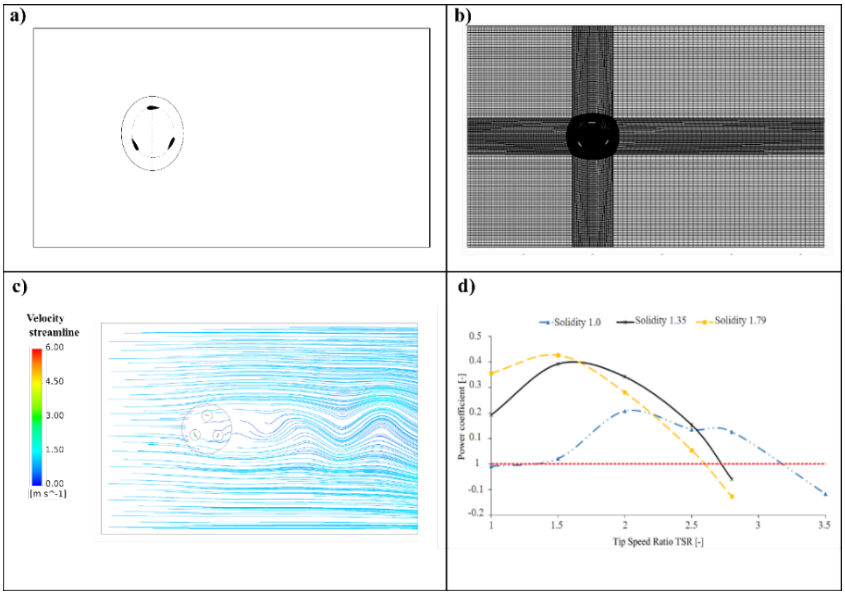
Hydrokinetic turbines have been presented nowadays as an energy alternative for the generation of electric energy, where the installation of dams and high civil works is not required, as they are installed directly in the river (Ibrahim et al., 2018). The correct sizing of the turbines, depending on the water conditions of the installation point, is essential to obtain an effective solution for a specific point (Gosselin et al., 2016; Guevara-Munoz et al., 2023). To achieve this, studies must be carried out by means of simulation tools, which allow for variations in blade size and tangential velocities, which will specify the best operating points for each turbine. Since this process requires a high computational cost, mathematical modeling strategies have been sought to obtain these operating points depending on the variation of the design conditions (Du et al., 2019; Patel et al., 2019).

These strategies start from the ANOVA statistical models, where it is required to perform a design of experiments to find, according to linear regression model, the equation that adequately and accurately represents the studied phenomena (Hatami et al., 2015; Rueda-Bayona et al., 2022). In addition to finding these operating points, the implementation of statistical analysis allows to directly evaluate which are the variables that impact the design of the turbines, and therefore have relevance in the studies. From these models it is possible, therefore, to analyze the impacts of the variables both individually along with the combined effects. Several studies have determined that the main variables of this type of turbines are solidity which relates the number of blades, chord and turbine radius, and TSR which relates the speed of the turbine in terms of its radius and the flow conditions, it is for the reason that in this study the solidity and TSR are taken as the main variables or factors, and the output will be the power coefficient (Çetin et al., 2005; Mohamed, 2013; Tobon-Tobon et al., 2020).

The objective of this study is to evaluate various regression models in estimating the power coefficient of a H-Darrieus hydrokinetic turbine, considering variations in solidity and Tip Speed Ratio (TSR). The objective is to identify the optimal regression model that can accurately represent the turbine's performance, allowing for the prediction of its behavior without requiring extensive simulations. Where the data used to the implementation of the regression models, are from previous studies that analyze the relationship between solidity, TSR, and power coefficient in H-Darrieus turbines (Guevara-Munoz et al., 2023). Figure 2 shows a graphical summary of the base study, from which the factors (solidity and TSR) and the response variable (power coefficient) are obtained. Figure 2 a) shows the 2D simplified H-Darrieus turbine geometry. Figure 2 b) depicts the discretization process. Figure 2 c) shows the results obtained by CFD. Finally, Figure 2 d) shows the power coefficient curves for each solidity.

Figure 2

Summary of the base study methodology.



Source: Taken from (Guevara-Munoz et al., 2023).

Research Results

Table 1 shows the simulation results along with the variables of each of the simulations provided by the design of experiments. Based on these data, we proceed to evaluate the regression models where the variation of the variables in their individual and composite terms will be carried out in order to find the combination of factors that best represents the calculation of the Cp in terms of Solidity and TSR. These models are shown in Table 2, where the linear and quadratic terms are implemented, including the interactions between them to a level of four order, which allows to explore linear and non-linear relationships between the variables and the response.

Table 1

Simulation results of the Desing of Experiments (DoE).

Solidity	TSR	CP	Solidity	TSR	CP	Solidity	TSR	CP
1.0	1.5	0.021	1.35	1.5	0.392	1.79	1.5	0.427
	2	0.207		2	0.342		2	0.281
	2.5	0.136		2.5	0.153		2.5	0.054
	3	0.126		3	-0.060		3	-0.127
	3.5	-0.117		3.5	-0.643		3.5	-0.564

Source: Taken from (Guevara-Munoz et al., 2023).

Table 2

Implemented regression models.

Model	Model terms								
	SLD	TSR	$SLD \cdot TSR$	SLD^2	TSR^2	$SLD^2 \cdot TSR$	$SLD \cdot TSR^2$	$SLD^2 \cdot TSR^2$	TSR^3
1									
2									

3									
4									
5									
6									
7									
8									
9									
10									
11									
12									
13									
14									
15									

Source: authors own development.

After programming the models in the Rstudio® software, they are evaluated according to the corrected Akaike information criterion (AICc) and the Bayesian information criterion (BIC). Where of the AICc represents the evaluation of the relative quality of the models according to the number of parameters evaluating the overfitting, being the smallest value the model that indicates the best fit. Moreover, the BIC allows to find the simplest model that adequately represents the system. The results of this evaluation are shown in Table 3. From this analysis it is found that the model that most adequately represents the problem described is the number eight which includes the linear elements, the interaction between the variables and the quadratic terms that fit the problem in a coherence and simple way.

Table 3

Evaluation of the implemented regression models.

Model	AICc	AICC order	BIC	BIC order	Final order
1	14.8	13	14.75	15	28
2	-1.3	3	-1.36	13	16
3	2.23	8	1.06	14	22
4	-1.11	4	-4.24	11	15
5	4.7	10	-1.55	12	22
6	-6.3	2	-12.56	7	9
7	1.15	6	-9.89	8	14
8	-10.43	1	-28.77	3	4
9	10.79	12	-7.55	10	22
10	1.98	7	-27.64	5	12
11	17.87	14	-30.05	2	16
12	3.51	9	-14.83	6	15
13	0.96	5	-28.67	4	9
14	10.57	11	-7.77	9	20
15	48.55	15	-31.66	1	16

Source: authors own development

In Table 4 the analysis of variance shows the influence of the study factors on the estimation of power coefficient (response variable), where the P value indicates that all values are significant, meaning that they have a direct influence on the determination of the CP. It can be seen that the factor with the highest significance is the TSR, where the solidity factor, which has a relatively high P-value, must also be included in the analysis in an attempt to include the order 2 effects.

Table 4

ANOVA analysis.

Response: CP	Df	Sum Sq	Mean Sq	F value	Pr(>F)
SLD	1	0.00891	0.00891	2.3408	0.1645532
TSR	1	0.90793	0.90793	238.5726	3.07e-07 ***
ST	1	0.18922	0.18922	49.7210	0.0001070 ***
S2	1	0.00040	0.00040	0.1063	0.7527573
T2	1	0.13978	0.13978	36.7303	0.0003024 ***
S2T	1	0.09788	0.09788	25.7191	0.0009633 ***
Residuals	8	0.03045	0.00381		

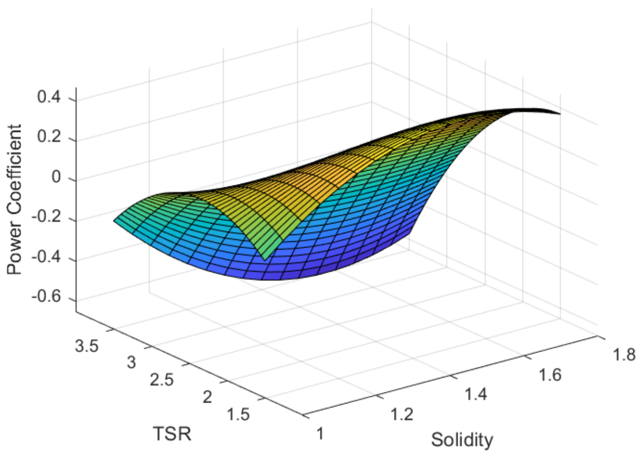
Source: authors own development.

From the ANOVA analysis it is possible to determine the fit coefficients that correspond to each term of the equation, in order to guarantee that the prediction equation adequately represents the studied problem. The prediction equation is shown in Eq 1 presenting an R^2 of 0.98 which is acceptable for this type of implementation. Eq 1 is further evaluated in order to obtain the maximum value of Cp. Figure 2 shows the surface obtained in the evaluation where it can be observed that the maximum value is found for a solidity of 1.55 and a TSR of 1.5, which represents a Cp of 0.4704.

$$CP = -9.21286 + 12.00993 * SLD + 4.41996 * TSR - 4.91456 * SLD * TSR - 3.87085 * SLD^2 - 0.23076 * TSR^2 + 1.57702 * SLD^2 * TSR \quad (1)$$

Figure 2

Evaluation of the prediction equation.



Source: authors own development

Conclusions

Regression models based on design of experiments prove to be effective in the process of predicting power coefficients in the design process of hydrokinetic turbines, where it is possible to obtain the optimum design conditions within the range of observation. This allows to reduce widely the amount of simulations that must be carried out for the numerical evaluation that this type of designs requires, where it is possible from the obtained equations to know the behavior of the turbine from the change in the analyzed input variables. As future work it is expected to obtain a robust model that allows to analyze in a wide way the design of hydrokinetic turbines departing of a mathematical model, which allows to reduce the design times, finding efficient solutions.

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