Determination of parameters affecting aerodynamic performance in S833 airfoil

Burak Çanakçı¹ · Uğur Çakır¹ · Ayhan Aytaç¹

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Abstract

This study presents the investigation of the factors affecting the performance of the airfoil, which is supposed to be used in a low power wind turbine. Airfoil surface roughness, angle of attack and wind speed parameters and interactions between these parameters affect performance. The conditions that the airfoil will be exposed to in the field of use can be modeled in the wind tunnel beforehand, and its performance in working conditions can be predicted. For this purpose, the airfoil model prepared using a three-dimensional printer can be tested in the wind tunnel, and the most effective parameter on performance can be determined. With the factorial design method used differently from the literature, performance analysis can be performed without the need for long mathematical calculations and analyzes. As a result, the most effective parameter on the performance is found as the surface roughness from the experimental design model created according to the selected factor levels. The second important parameter is the angle of attack-surface roughness binary factor interaction.

Keywords S833 airfoil · C_L/C_D ratio · 2^k factorial design · Aerodynamic performance · Surface roughness

1 Introduction

The first and most important factor that makes these turbines operate in the most efficient way is the shape of the airfoil to be used in the design. The conditions under which a wind turbine with a design phase has been completed will have to be taken into account in order to be able to work most efficiently during its lifetime. Due to environmental influences such as insect adhesion, dust, dirt, frost, corrosion, etc., disruption and roughness of the turbine airfoils are formed. However, contrary to expectations, roughness can also lead to an increase in wing performance in some cases. There are many studies in the literature on the determination of parameters that are effective on airfoil performance.

Since the contamination effect on the wing is the primary influencing factor on performance, most studies

have focused on this issue. Environmental influences such as sand storms or icing on the wing surfaces cause deterioration of the wing surface quality. Impairments and roughness increases in airfoil surfaces increase aerodynamic resistance and consequently cause reducing turbine power [1–3]. These impurities have been modeled and investigated on the surface of the models created in wind tunnels (eg NACA 63-418 airfoil etc.) in order to realize the difficulties caused by the examination of these deterioration and wear in real conditions and to take measures against these effects [4]. It is an important alternative in numerical methods in performance analysis to eliminate the difficulties created by experimental conditions. In a numerical study, it has been determined that the rains that are large enough to cover the surface of the airfoil have little effect on the performance and the rains at low frequencies change the performance [5]. In a

✉ Ayhan Aytaç, aytac@kho.edu.tr; Burak Çanakçı, bcanakci@kho.edu.tr; Uğur Çakır, ugurcakir@gmail.com | ¹National Defense University, KHO, Ankara, Turkey.

study on the NACA 6 series airfoils, the level of contamination on the surface was changed from the front edge to the rear edge and a reduction in lift coefficient up to 35% was observed in the critical angle of attack [6]. As it can be understood from here, most of the recent research has been concerned with the regions and at what rate rather than the occurrence of pollution. In numerical and experimental researches on the roughness effect occurring at different positions on different airfoils such as DU 95-W-180, DU 96-W-180, the increase in the leading edge roughness has decreased performance [7, 8]. In the examinations carried out on the NACA 63-415, NACA 23012 and E387 airfoils, sensitive areas leading to loss of performance against roughness were determined and did not affect the performance after a certain roughness value. In fact, it has been determined that certain roughness values added to the airfoil bottom surface provide an increase of 8.62% in the buoyancy [9–11].

In addition to roughness, there are different parameters affecting aerodynamic performance. For example, how an object in the flow field is affected by a different object in the same flow field and flow direction. NACA 2415, NACA 0012 series were investigated how the performance of the blades changed with the cylindrical rods placed within the same flow area and at certain distances to the front of the wing in the direction of the flow. As a result of the control of flow separation with the CFD simulations carried out, friction reductions of up to 61% have been achieved, thus an increase in airfoil performance [12, 13]. Another innovative method that can be used to investigate these factors is artificial neural network method. Using this method, optimal results can be achieved with a neural network model to be established without much experimentation. In the study investigating the effect of a cylinder placed in the same flow area with the NACA 0012 airfoil on the wing performance with ANNs (the ANN artificial neural networks) method; parameters such as cylinder diameter, distance between cylinder and wing were simulated numerically with the neural network model and in the optimized conditions, the C_L/C_D ratio (the C_L dimensionless lift coefficient, the C_D dimensionless drag coefficient) increased by 178% [14].

In our study, a performance analysis method different from the methods mentioned above was used. Statistical-based experimental design techniques are widely used to investigate and improve the effects of the effects of different parameters on process performance. The main difference that separates the study from the literature surveys mentioned above is that full factorial experimental design method has been used. Full factorial experiments are used to accurately evaluate the main and quadratic interaction effects of experimental factors on target compounds [15]. Thus, the full factorial experimental design gives a more

practical and reliable result than fractional factorial experiments such as Taguchi [16]. Factorial design is also advantageous in terms of investigating interactions or changes between factors [17]. The most important factor that distinguishes factorial designs from internal designs is that all of the levels of any factor used in the experiment are identical at each level of other factors [18]. As it is here, in cases where two or more factors are handled, factorial design is a powerful technique.

When each replay is completed in a factorial experiment, all possible combinations of all levels of all factors are examined. The effect of a factor is defined as the change in factor level composed by the response. This is the main effect. Factorial experiments are the only way to determine the interaction between variables [19].

In the literature, there is no study on the airfoils performance analysis using factorial experimental design method. A new model was defined by minimizing the effects of uncontrolled factors. The accuracy of the model was confirmed by verification experiments. This study is original in the literature as the first study in which the full factorial experimental design method is used in the analysis of the airfoil performance analysis.

In the study, firstly, performance parameters of the airfoils are mentioned. Then, the production stages of the airfoil selected for analysis are explained and the experimental setup is introduced. The regression equation obtained from the experimental results performed according to the last experimental design matrix has been revealed, the interaction analyzes of the parameters have been made and the verification experimental results have been presented.

2 Materials and methods

In this study, the S833 airfoil developed by the National Renewable Energy Laboratory (NREL), which is intended to be used in a low-power wind turbine, has been used. The whole surface of the airfoil was covered with 2 mm. thick coating material to model the contamination that the airfoil is exposed to under operating conditions. Rough and smooth airfoils under the same conditions were subjected to tests at different wind velocities and angle of attack in the subsonic wind tunnel. By using 2-level full factorial experimental design model, the effects of surface roughness, angle of attack and wind speed parameters on aerodynamic performance and interaction between parameters were investigated.

Fig. 1 S833 airfoil geometry

2.1 Aerodynamic performance parameters of airfoils

As the current on the airfoils is often close to two-dimensional, it is sufficient to examine the flow properties around the flow around a single cross-section as the flow characteristics remain the same in all sections along the airfoil [20]. Airfoil cross-sectional geometry is shown in Fig. 1.

2 force (drag-carry or lift) component and 1 moment (pitching moment) component are acting on the airfoil. The lift force and pitching moment are generally dependent on the pressure distribution across the airfoil surface. The drag force depends on both the pressure and friction distribution along the surface. Because of the different shapes and dimensions of the airfoils developed for various purposes, dimensionless coefficients are taken into consideration in the comparisons and evaluations [20].

C_L eq. (1) and C_D eq. (2) taken into account in the performance evaluation of the airfoils were calculated in two dimensions as follows. Other terms in the equation are L (the L lift force), D (the D drag force), V (the V wind speed), ρ (the ρ fluid density), S (the S airfoil surface area). After calculating these coefficients without dimension, the C_L/C_D ratio can be used practically for performance comparisons [20].

$$C_L = \frac{L}{(1/2)\rho V^2 S} \quad (1)$$

$$C_D = \frac{D}{(1/2)\rho V^2 S} \quad (2)$$

2.2 Modeling and production of S833 airfoil

S833 airfoil used in experimental studies had 200 mm × 200 mm. size was developed by NREL using coordinates was a computerized model and Fortus 250 MC 3D Printer is produced with ABS material (Fig. 2). The airfoil is connected to the wind turbine by a metal shaft

Fig. 2 Produced airfoil **Fig. 3** Wind tunnel

of 11 mm diameter fixed to the 6 mm. diameter hole on its side surface.

2.3 Wind turbine and 3-way balancer

Experimental studies have been carried out in the sub-sonic wind tunnel TecQuipment AF 100 (Fig. 3) at the maximum wind velocity of 37 m/s. The tunnel has an inspection section of 300 × 300 × 600 mm. The three-component balancer (Lifting Force, Drag Force and Pitching Moment) was used for load measurements. The data measured in the experimental studies were collected by the Versatile Data Acquisition System (VDAS) integrated in the wind tunnel.

Fig. 4 Coating process applied to the surface of the airfoil **Table 1** Factors and levels

Factors	Name	Lower level	High level
A	Wind speed	10 m/s	37 m/s
B	Angle of attack	5°	12°
C	Surface roughness	Clean surface	Coated surface

3 Test results and discussion

In the first experiments, airfoil was tested at 2 different wind speeds and 2 different angles of attack under clean surface conditions and then 2 mm thickness coating material simulating surface roughness was applied to the surface of the airfoil (Fig. 4) and the tests were repeated under the same conditions.

As the speed value in the tests, the maximum speed of the wind tunnel is 37 m/s and close to the operating conditions 10 m/s was used. As an angle of attack, as a result of trials, the aerodynamic performance was highest 12° and a low angle of attack value of 5° was selected for comparison. Information for the levels of the selected factors was given in Table 1. 2^k factorial (the 2^k two level full factorial design) experimental design model was used to examine the parameters effecting the airfoil performance and their interactions with each other. In this design model, wind speed, angle of attack and surface roughness were considered as k (the k factors) parameters. The experimental design matrix was created for the selected two levels of the factors to be investigated, the effect of the airfoil on the performance of C_L/C_D coefficients. The matrix generated by using the Minitab 18 statistical software program using the coding method was presented in Table 2. In the experiments, lifting, drag forces were collected by VDAS program and C_L lifting coefficient, C_D drag coefficient and C_L/C_D ratio were calculated. The test results were given in Table 2.

3.1 Regression and variance analysis results

Multiple regression analysis; As a result of the experiments, backward extraction method was used by using

Table 2 Full factorial experimental design matrix

Number of experiments	Factors and levels (coded)			C_L/C_D
	A	B	C	
1	−1	−1	−1	2.75
2	−1	−1	+1	1.33
3	−1	+1	−1	4.62
4	−1	+1	+1	1.43
5	+1	−1	−1	1.4
6	+1	−1	+1	1.25
7	+1	+1	−1	4.4
8	+1	+1	+1	1

8 values (2^3 full factorial) obtained for two levels of each parameter. In the regression analysis, it was aimed to explain the relationship between the variables functionally and to define this relationship with a model [16].

In the first stage, all the main parameters, the binary interactions of the parameters and the interaction caused by the three were included in the model. According to the experimental design matrix established as a result of the analysis performed using the Minitab-18 program; pareto and normal distribution graphs were formed at $\alpha=0.10$ significance level. In the pareto graph analysis for factors and binary interactions, the factors that exceed the threshold value of 2.132, which is the significance level of 0.1, were the factors that affect the wing performance most. As the graph shows (Fig. 5), the most important factor is the surface roughness, the second important factor is the angle of attack-surface roughness binary interaction and the third important factor is the angle of attack. Factors that have the least effect on the system, wind speed-surface roughness and wind speed-angle of attack are binary factor interactions. These factors with the least effect were not included in the model by the regression analysis program.

In the multiple regression analysis performed using Minitab-18 program, backward extraction method was used by using 8 values (2^3 full factorial) obtained for two levels of each parameter as a result of the experiments. In the first stage, all the main parameters, the binary interactions of the parameters and the interaction caused by the three are included in the model. However, in order to

Fig. 5 Pareto chart of the standardized effects

obtain sufficient degree of freedom at the beginning, the step-by-step procedure did not influence the wind speed-angle of attack and wind speed-surface roughness of the interactions determined by the binary interactions were not included in the analysis. $\alpha = 0.1$ significance level (confidence) according to the p values determined for each factor in the analysis performed step by step; the most effective parameter on wing performance ($p = 0.005 < 0.1$) was the surface roughness factor. The second important factor was found to be the angle of attack-surface roughness double interaction ($p = 0.025 < 0.1$). The speed factor, which is the least important factor in the analysis, was removed from the model in step 3. The ratio of the model to the relationship between variables (change in C_L/C_D ratio) was calculated as $R^2 = 93.26\%$ (R^2 (corrected)) = 88.2%). The results of the regression analysis were presented in Table 3.

According to the results of the regression analysis, the variance (anova) analysis was performed to analyze the significance of the contribution of each variable to the model at $\alpha = 0.1$ significance level. The results of analysis of variance were presented in Table 4. The significance level of the model for the factors was found to be $p = 0.008$ and the F test statistic were 18.44. There were no factors to be excluded from the model when the level of significance of all the factors that constitute the model is examined in the same way. For binary interactions, $p = 0.025$ and F were obtained as test statistic 12.22.

In order to determine the coefficients of regression eq. (3) t -test was applied. The results of the T -test and the coefficients obtained were presented in Table 5. The effects of the factors in the model were seen here. Impact values, positive signfactor (angle of attack main factor impact

Table 3 Multiple regression analysis results

	Step 1		Step 2		Step 3	
	Coef	P	Coef	P	Coef	P
Constant	2.273		2.273		2.273	
Wind speed	-0.260	0.155	-0.260	0.166		
Angle of attack	0.590	0.037	0.590	0.026	0.590	0.030
Surface roughness	-1.020	0.013	-1.020	0.006	-1.020	0.005
Angle of attack $\times$ Surface roughness	-0.628	0.033	-0.628	0.022	-0.628	0.025
Wind speed $\times$ Angle of attack $\times$ Surface roughness	-0.185	0.253				
S		0.329014		0.404269		0.507715
R-sq		98.58%		96.79%		93.26%
R-sq (adj)		95.04%		92.52%		88.20%
R-sq (pred)		77.34%		77.20%		73.02%

Table 4 Results of variance analysis

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	3	14.258	4.7527	18.44	0.008
Linear	2	11.108	5.5540	21.55	0.007
Angle of attack	1	2.785	2.7848	10.80	0.030
Surface roughness	1	8.323	8.3232	32.29	0.005
2-way interactions	1	3.150	3.1501	12.22	0.025
Angle of attack × Surface roughness	1	3.150	3.1501	12.22	0.025
Error	4	1.031	0.2578		
Total	7	15.289			

value = 1.180) positive effect on performance, negative sign factors (surface roughness main factor impact value = −2.040, angle of attack × surface roughness binary interaction impact value = −1.255) reduces performance. In the analyzes, regression equation was obtained including the factors that were found to be effective in performance.

Regression equation:

$$C_L/C_D = 2.273 + 0.590 \text{ Angle of attack} - 1.020 \text{ Surface roughness} - 0.628 \text{ Angle of attack} \times \text{Surface roughness} \quad (3)$$

Table 5 T-test results and regression equation coefficients

Term	Effect	Coef	SE Coef	T-Value	P-Value	VIF
Constant		2.273	0.180	12.66	0.000	
Angle of attack	1.180	0.590	0.180	3.29	0.030	1.00
Surface roughness	−2.040	−1.020	0.180	−5.68	0.005	1.00
Angle of attack × Surface roughness	−1.255	−0.628	0.180	−3.50	0.025	1.00

As can be seen in the analysis and the regression equation obtained, the wind speed factor was not taken into account because of the low confidence level value ($\alpha = 0.10$). However, in order to see the effect of the wind speed parameter, which has a significant effect on the design and selection of wind turbines, on the wing performance, the analysis was repeated by selecting the confidence level $\alpha = 0.17$. When the normal distribution of the new analysis and the pareto graphs (Fig. 6) were examined, the speed factor was at the immediate boundary of the 1.798 line which was the threshold value of 0.17 significance level. The most effective factor for the newly installed model was surface roughness and the second important factor was the angle of attack-surface roughness binary interaction.

In the new multiple regression analysis, when the p values obtained in the second step were examined, the most effective factor was the surface roughness while the second important factor was the angle of attack-surface roughness of the double factor interaction (Table 6). For installed model $R^2 = 96.79\%$ (R^2 (corrected) = 92.52%)

Fig. 6 According to the new analysis; pareto chart of the standardized effects

Table 6 Renewed regression analysis results

	Step 1		Step 2	
	Coef	P	Coef	P
Constant	2.273		2.273	
Wind speed	−0.260	0.155	−0.260	0.166
Angle of attack	0.590	0.037	0.590	0.026
Surface roughness	−1.020	0.013	−1.020	0.006
Angle of attack × Surface roughness	−0.628	0.033	−0.628	0.022
Wind speed × Angle of attack × Surface roughness	−0.185	0.253		
S		0.329014		0.404269
R-sq		98.58%		96.79%
R-sq (adj)		95.04%		92.52%
R-sq (pred)		77.34%		77.20%

Table 7 Renewed variance analysis results

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	4	14.7989	3.6997	22.64	0.014
Linear	3	11.6488	3.8829	23.76	0.014
Wind speed	1	0.5408	0.5408	3.31	0.166
Angle of attack	1	2.7848	2.7848	17.04	0.026
Surface roughness	1	8.3232	8.3232	50.93	0.006
2-way interactions	1	3.1500	3.1500	19.27	0.022
Angle of attack × Surface roughness	1	3.1500	3.1500	19.27	0.022
Error	3	0.4903	0.1634		
Total	7	15.2892			

is obtained. As can be seen, the relationship between the variables description rate of the new model increased.

The results of the variance analysis performed for the new model revealed the contribution levels of the variables to the model. When the *p*-value of the model obtained by the variation analysis (*F*-test) was examined ($p = 0.014 < 0.17$) one or more effects can be deduced (Table 7).

New regression equation:

$$C_L/C_D = 2.273 - 0.260 \text{ Wind speed} + 0.590 \text{ Angle of attack} - 1.020 \text{ Surface roughness} - 0.627 \text{ Angle of attack} \times \text{Surface roughness} \quad (4)$$

As a result of renewed analysis, it was seen that the speed factor in the regression eq. (4) obtained has a very low effect value compared to other factors and it decreases the performance due to the fact that the coefficient (−0.260) is negative (Table 8).

When the normal distribution and pareto graphs of the newly developed model were examined, it was found that the speed factor was at the boundary of the threshold value of 1.178, which is the confidence value of 0.17 and the effect was lower than other factors. However, due to the fact that the effect of wind speed on the performance is one of the factors investigated, the new regression equation will be taken into consideration.

3.2 Verification tests

Verification tests were performed to check the accuracy of the new regression equation. Firstly, the predictions for C_L/C_D ratio were made according to the regression equation obtained for the three selected parameter (wind speed, angle of attack, and surface roughness) values.

The C_L/C_D ratio was obtained as 1.215 with the regression equation as a result of the first prediction (Table 9).

Table 8 T-test results and new regression equation coefficients

Term	Effect	Coef	SE Coef	T-Value	P-Value	VIF
Constant		2.273	0.143	15.90	0.001	
Wind speed	−0.520	−0.260	0.143	−1.82	0.166	1.00
Angle of attack	1.180	0.590	0.143	4.13	0.026	1.00
Surface roughness	−2.040	−1.020	0.143	−7.14	0.006	1.00
Angle of attack × Surface roughness	−1.255	−0.627	0.143	−4.39	0.022	1.00

Table 9 First predict values and results

Variable		Setting	
Wind speed		0	
Angle of attack		1	
Surface roughness		1	
Fit	SE Fit	95% CI	95% PI
1.215	0.285861	(0.305262; 2.12474)	(−0.360713; 2.79071)

Table 10 Second predict values and results

Variable		Setting	
Wind speed		1	
Angle of attack		0	
Surface roughness		−1	
Fit	SE Fit	95% CI	95% PI
3.0325	0.247563	(2.24464; 3.82036)	(1.52387; 4.54113)

Table 11 Third predict values and results

Variable		Setting	
Wind speed		−1	
Angle of attack		0	
Surface roughness		1	
Fit	SE Fit	95% CI	95% PI
1.5125	0.247563	(0.724644; 2.30036)	(0.0038700; 3.02113)

Fig. 7 Effect of main factors on performance graphs

All displayed terms are in the model.

Since the rate of variance of the regression equation in the C_L/C_D ratio was 92.52%, it was predicted that the predictive value would deviate by approximately 7.48% from the experimental results obtained. The testing of the first predictive results showed that the C_L/C_D ratio ranged between 1.13 and 1.12.

As a result of the second prediction (Table 10), the C_L/C_D ratio was found to be 3.0325. The values obtained from the verification tests ranged between 3.17–3.33.

As a result of the third prediction (Table 11), the C_L/C_D ratio was found to be 1.5125. The values obtained from the verification tests ranged between 1.42–1.50.

All three estimates were consistent with experimental data. The values found in the verification test were within the limits of the prediction.

3.3 Factor impact assessments and surface graphs of factor interactions

The graphs of the effects of main factors (Fig. 7) on response (wing performance) were given below. Wind speed, surface roughness and angle of attack were the factors investigated on performance. There was a slight decrease in performance with the increase of the wind speed parameter. Increase in the angle of attack was observed to increase performance. With the increase in surface roughness value, a significant decrease in performance was observed. Surface roughness delays the stall angle and decreases the lift [4, 16].

When the binary interaction graphs of the factors (Fig. 8) were examined, the effects of the lower and upper-level values of the factors on the result variable

Fig. 8 Binary factor interaction graphs

A gray background represents a term not in the model.

and interactions between the two factors can be determined. Wind speed-angle of attack and wind speed-surface roughness in binary interaction graphs, level of curves were close to parallel to each other. This indicates that there is no significant interaction between these factors.

Angle of attack-surface roughness in binary interaction graph, with the increasing angle of attack and decreasing surface roughness, the curves moved away from parallelism. This indicates a binary interaction between the angle of attack and the surface roughness factors.

Wind speed-angle of attack in binary interaction; it was observed that the increase in wind speed is more effective on performance in terms of low angles of attack (decrease in performance). The effect of surface roughness is at the foreground in binary interaction between wind speed and surface roughness.

When the surface roughness was high, the wind speed had almost no effect on performance. In the case of low surface roughness, there was a slight decrease in performance with increasing wind speed. The interaction between the angle of attack and the surface roughness was the most effective binary interaction on performance. At high surface roughness, the increase in angle of attack did not affect wing performance much. At low surface roughness, the increase in angle of attack affected approximately twice the performance (increase in performance). Since the angle of attack and the surface roughness is the main factor, they have been effective for performance, but the effect of their interaction with the wind speed has been quite low. Because the best performance value was obtained at low wind speeds in both interactions. This can be explained by the fact that the selected airfoil is suitable

for use in low-power wind turbines, at relatively low wind speeds, at small wing sizes (or less than 3 m. at low turbine rotor diameters). It has been explained above that surface roughness was the most effective factor on performance [4]. Surface roughness-velocity binary interaction; the effect of the wind speed on the performance of the rough surface was very low. Increasing speed was created a loss of performance on the clean surface. On the other hand, angle of attack-wind speed interaction; the speed increase was created loss of performance regardless of the angle of attack.

The surface graphs of the design and the contour curve graphs were given below for binary interactions. The three-dimensional surface graph of the surface roughness-angle of attack binary interaction was shown in Fig. 9. Due to the interaction between the surface roughness and the angle of attack, it was seen that the C_L/C_D response

Surface Plot of C_L/C_D vs Surface Roughness; Attack Angle **Fig. 9** Three-dimensional surface graph of the effect of surface roughness-angle of attack interaction on wing performance

function plane was skewed. This situation shows that the surface roughness and angle of attack binary interaction were the most effective binary factor interaction on performance.

The graphs for the contour curves (Fig. 10), which define the surfaces in the three-dimensional surface graphs, were shown above. The contour curve graphs support the interaction between the surface roughness-angle of attack of the most effective binary factor interaction.

The results obtained are important in terms of shedding new light on the researches since there is no such study in the literature. In addition, in parallel with the results presented in the literature, it has emerged as the surface roughness of the most effective parameter [9–11]. The point that makes the study different from the literature is that it is revealed in its interactions between parameters.

4 Conclusion and suggestions

In this study, 2^k factorial experimental design method was used in order to evaluate the parameters affecting the aerodynamic performance of S833 airfoil. Wind turbine blades are generally under different operating conditions. Surfaces are subject to deterioration with the effect of natural working conditions.

Most of the time, the surface smoothness is lost due to waste. To model this situation, the surface of the airfoil is covered with a rough material. Wind speed, surface roughness and angle of attack were factors to investigate the impact on performance. Analyzes were made

according to the experimental results for two levels of the factors. The effects of these factors on airfoil performance and interactions between each other were examined.

This study is the first in terms of the method used on airfoil performance analysis studies. In this maintenance, the study aims to make a unique contribution to the literature. As a result of the study;

At $\alpha=0.1$ confidence level, the rate of explanation of the change in the system in the regression model was 88.2%. A new regression model was established with $\alpha=0.17$ confidence level and wind speed parameter was included in the model. The rate of definition of the change in C_L/C_D ratio of the new regression model was obtained as 92.52%.

The most effective parameter on the airfoil performance is surface roughness. At both wind speeds; the clean surface airfoil performance is twice as good at the low angles of attack compared to the coated airfoil surface. The performance at high angles of attack is up to four times higher.

The second most effective factor on performance is the angle of attack-surface roughness binary factor interaction. The performance of the surface coated airfoil is reduced by approximately twice the increase in the angle of attack.

The angle of attack is the third important factor on performance. A positive increase in angle of attack has a positive effect on airfoil performance.

The least effect on performance is the wind speed. As it is understood from the coefficient in regression equation, it decreases performance.

Fig. 10 Contour plots of binary interactions of factors

Other factors; There are no significant effects on the result variable of the wind speed-angle of attack-surface roughness triple interaction, wind speed-surface roughness binary interaction, wind velocity-angle of attack binary interaction and they are not included in the regression model.

When the main factor was examined; the increase in wind speed reduces performance in both airfoil surfaces. Increase in angle of attack positively affects performance. Particularly at high wind speeds, an increase in the performance of clean surface airfoil was achieved. The increase in surface roughness is a parameter that has a negative effect on performance. In terms of high wind speed and angle of attack, a performance loss of up to fourfold was observed.

If the effect of a factor on the response variable depends on the value of the other factor, it can be considered that there is interaction between the two factors. In wind speed-angle of attack and wind speed-surface roughness, there is no significant interaction between factors. In the interaction of angle of attack-surface roughness; the improvement in surface quality with increased angle of attack results in a performance increase of approximately two times. While the angle of attack and the surface roughness are effective in the performance as the main factor, the effects of their interaction with the wind velocity are quite low. Because the change in wind speed does not make a major difference in performance compared to the change in surface condition and angle of attack. In the verification tests for checking the accuracy of the regression model, values were obtained within the estimated ranges.

The most important limitation that limits our study is the acceptance that all areas of the airfoil surface will be exposed to an equal level of pollution. In the working conditions, there was no equal amount of contamination or deterioration at each point on the airfoil surface [16]. Different scales of roughness can be applied to different parts of the airfoil surface and their effects on aerodynamic performance can be investigated [16]. Which surface areas are more susceptible to contamination can be determined by critical roughness amounts.

Furthermore, it is possible to investigate the applicability of special surface treatments to the surface during the manufacturing phase, which will minimize the possible distortion on the airfoil surface. The period during which the surface pollution will reach the critical level can be determined. For this purpose, researches can carry out on the planning and implementation of periodic cleaning procedures. On the other hand, the optimum conditions for the selected airfoil can be determined and the physical conditions at which the highest efficiency will be obtained can be determined.

Compliance with ethical standards

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

Research involving human participants and/or animals The authors certify that the current research does not involve human participants and/or animals.

Informed consent The authors certify that they have/grant an informed consent.

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