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Investigation of a rib structure effect on the aerodynamic performance of a plain flapped symmetrical airfoil

Bir düz flaplı simetrik kanat profilinin aerodinamik karakteristiğine kiriş yapısı etkisinin incelenmesi

***Yazar(lar) (Author(s))**: Ahmet Fatih KAYA*

ORCID: 0000-0002-7888-0250

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Investigation of a Rib Structure Effect on the Aerodynamic Performance of a Plain Flapped Symmetrical Airfoil

Highlights

- *A rib structure effect on the performance of a plain flapped symmetrical airfoil was examined numerically.*
- *The Spalart-Allmaras turbulence model was selected for numerical analyses.*
- *Aerodynamic performances of created designs were compared.*

Graphical Abstract

There are four different models were designed: $M1$ (NACA 0018 airfoil), $M2$ (airfoil with a rib structure), $M3$ (airfoil with a plain flap) and $M4$ (airfoil with a rib structure and plain flap). Their aerodynamic performances were compared in terms of lift-to-drag ratio (C_L/C_D).

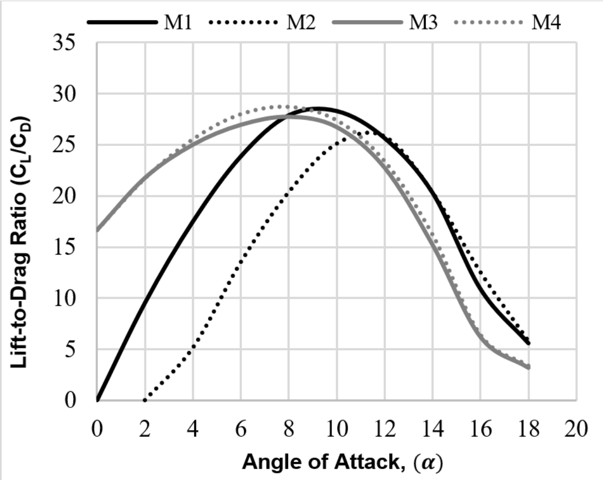

Figure. Lift-to-Drag ratios (C_L/C_D) of created models

Aim

It was aimed to investigate a rib structure's effect on the aerodynamic performance of a plain flapped airfoil.

Design & Methodology

Numerical analyses were performed using the Spalart-Allmaras turbulence model. After reaching the mesh independency, the validation process was carried out. Then, two-dimensional Computational Fluid Dynamics (CFD) analyses were conducted to compare different models in terms of their aerodynamic characteristics.

Originality

There is no paper has been found that examines the rib effect on the performance of a plain flapped symmetrical NACA 0018 airfoil.

Findings

The rib structure increased the aerodynamic performance of the plain flapped airfoil at $\alpha > 2°$.

Conclusion

As a result, it was seen that using the rib structure on the plain flapped airfoil increased the aerodynamic performance at almost all attack angles. So, using the rib structure may be an effective way to increase the performance of airfoils or wind turbines.

Etik Standartların Beyanı (Declaration of Ethical Standards)

The author(s) of this article declare that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission. (EN) / Bu makalenin yazar(lar)ı çalışmalarında kullandıkları materyal ve yöntemlerin etik kurul izni ve/veya yasal-özel bir izin gerektirmediğini beyan ederler. (TR)

Investigation of a Rib Structure Effect on the Aerodynamic Performance of a Plain Flapped Symmetrical Airfoil

Araştırma Makalesi / Research Article

Ahmet Fatih KAYA[1*]

[1]Teknoloji Fakültesi, Enerji Sistemleri Müh. Bölümü, Kocaeli Üniversitesi, Türkiye

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ABSTRACT

In this paper, two-dimensional computational fluid dynamics analyses were conducted to examine the rib effect on the performance of the NACA 0018 plain flapped airfoil. A mesh independence study was carried out and the Spalart-Allmaras turbulence model was selected for validation. Four various airfoil models were designed: M1 (airfoil without plain flap and rib structure), M2 (airfoil with rib structure), M3 (airfoil with a plain flap) and M4 (airfoil with a rib structure and plain flap). The performance of designed airfoils was calculated in terms of lift-to-drag (C_L/C_D) ratio. As a result, the plain flap significantly increased the lift coefficient (C_L) and drag coefficient (C_D). While the rib structure enhanced the aerodynamic performance of the non-flapped airfoil when the attack angle was greater than 12°, it increased the performance of the plain flapped airfoil at almost all attack angles. Furthermore, it was seen that the rib structure decreased C_D values of plain flapped airfoil at all attack angles and increased C_L values of plain flapped airfoil when the attack angle was greater than 2°.

Keywords: Numerical analysis, airfoil, plain flap, rib structure, drag coefficient, lift coefficient.

Bir Düz Flaplı Simetrik Kanat Profilinin Aerodinamik Karakteristiğine Kiriş Yapısı Etkisinin İncelenmesi

ÖZ

Bu çalışmada düz flapa sahip bir NACA 0018 kanat profilin aerodinamik performansına kiriş etkisi iki boyutlu olarak Hesaplamalı Akışkanlar Dinamiği yöntemi ile incelenmiştir. Ağ yapısından bağımsızlığa ulaşıldıktan sonra deneysel çalışma Spalart-Allmaras türbülans modeli ile doğrulanmıştır. M1 (düz flapsız ve kiriş yapısız kanat), M2 (kiriş yapısına sahip kanat), M3 (düz flaplı kanat) ve M4 (düz flaplı ve kiriş yapısına sahip kanat) olmak üzere 4 farklı kanat yapısı modellenmiştir. Kanatların aerodinamik performansları kaldırma katsayısının sürükleme katsayısına oranı (C_L/C_D) bulunarak hesaplanmıştır. Çalışmanın sonucunda düz flap yapısı, kaldırma katsayısı (C_L) ve sürükleme katsayısını (C_D) önemli ölçüde arttırmıştır. Kiriş yapısı düz flapa sahip olmayan kanadın aerodinamik performansını atak açısı 12°'den büyük olduğunda arttırmışken, flap yapısına sahip olan kanadın aerodinamik performansını neredeyse bütün atak açılarında yükseltmiştir. Aynı zamanda kiriş yapısı, bütün atak açıkarında düz flapa sahip olan kanatta gözlemlenen C_D değerlerini azaltmış ve atak açısı 2°'den büyük olduğu durumda C_L değerlerini arttırmıştır.

Anahtar Kelimeler: Sayısal analiz, kanat profili, düz flap, kiriş yapısı, sürükleme katsayısı, kaldırma katsayısı.

1. INTRODUCTION

The design of airfoils has become a crucial topic as the importance of renewable energy grows. Wind turbines are occasionally equipped with airfoils that are created for airplanes. Airplanes and wind turbines have different design criteria. In wind turbines, an airfoil can be used even reaching a stall angle or more. Furthermore, the lift-to-drag ratio is the most crucial variable for wind turbines [1]. However, for aircraft design, lowering the drag for a fixed lift efficiency might be the goal of the design process [2].

The impact of geometrical and operational variables on symmetrical and asymmetrical airfoils has been the subject of several research studies. Şahin and Acir investigated the lift and drag performances of the NACA 0015 airfoil experimentally and numerically. They used two different turbulence models in order to validate experimental results, k-epsilon and Spalart Allmaras. As a result of their study, they stated that the stall was started when the angle of attack (α) reached 16° [3]. Lopes and Alé examined the aerodynamic characteristics of the NACA 0018 airfoil. They used EasyCFD software to conduct numerical analyses and investigated different turbulence models. They found that the lift coefficient (C_L) was underpredicted by the k-epsilon model at almost all α values. In their study, the average error for C_L was only 2.1% with the shear stress transport (SST) turbulence model [4]. Chakroun and Bangga investigated the Gurney flap effect on the aerodynamic characteristics of an airfoil. They stated that using the Gurney flap increased both C_L and drag coefficient (C_D) values. Moreover, using the Gurney flap enhanced the

**Sorumlu Yazar (Corresponding Author)*
e-posta : ahmetfatih.kaya@kocaeli.edu.tr

aerodynamic performance of the wind turbine [5]. Hunsaker et al. examined the geometry and aerodynamic performance of parabolic flaps. The results show that at large flap-chord fractions, the parabolic flap can generate much less drag than a conventional flap [6]. Tanürün et al. numerically examined the rib structure effect on the performance of a wind turbine. They included a triangular rib on the trailing edge of the NACA 2412 airfoil. As a result of their study, they found that at higher α values, triangular rib structure enhances the aerodynamic performance. When α > 15°, the lift-to-drag ratio (C_L/C_D) was increased by utilizing the rib structure on the airfoil [7]. Venkatesan et al. investigated the effects of square, rectangle and triangle dimples on the NACA 2412 airfoil's aerodynamic behavior. They stated that the airfoil with the square dimple performs better than other airfoil designs [8]. Wang et al. the aerodynamic performances of different wind turbines equipped with different series airfoil shapes. They conducted two-dimensional numerical analyses. It was shown that the power coefficient could be raised by changing the maximum thickness point of an airfoil. [9]. Mohamed et al. investigated the performance of a wind turbine equipped with slotted airfoils. They stated that slotted airfoils can enhance efficiency at lower tip speed ratios (TSR). However, at higher TSR values, the aerodynamic performance of the turbine decreases. Furthermore, they saw that the self-start capability of the wind turbine equipped with slotted airfoils is far better than the base turbine [10]. A vortex generator height impact on an airfoil's aerodynamic performance was analyzed experimentally and numerically by Li et al. As a result, they found that the stall angle increased from 8° to 18° by using vortex generators. Furthermore, by using vortex generators, the maximum lift coefficient was increased by 48,7%. Moreover, vortex generators decreased the drag coefficient by approximately 85%. However, the authors stated that the maximum C_L/C_D ratio of the airfoil could not be increased by using vortex generators [11]. Villalpando et al. studied various turbulence models and aimed to detect the most reliable turbulence model to analyze the flow around a NACA 63-415 airfoil. They stated that the Spalart-Allmaras model performs better than other turbulence models [12].

This study aimed to investigate the rib structure effect on the NACA 0018 symmetrical airfoil with a plain flap. Numerical analyses were performed using ANSYS Fluent software. After the mesh independence test and validation study, C_L, C_D and C_L/C_D values of four different airfoil structures that are NACA 0018, NACA 0018 with rib structure, NACA 0018 with plain flap, and NACA 0018 with plain flap and rib structure were compared. No study has been found in the literature investigating the rib effect on the plain flapped symmetrical airfoil.

2. NUMERICAL MODEL

2.1.Basic Equations

Reynolds number (Re) can be expressed as [10];

$$Re = \frac{\rho U c}{\mu} \quad (1)$$

Here, ρ depicts the fluid density, U shows the fluid velocity, c depicts the chord length and μ represents dynamic viscosity.

Drag force (F_D) and lift force (F_L) can be shown as follows [3];

$$F_D = \frac{C_D \rho U^2 S}{2} \quad (2)$$

$$F_L = \frac{C_L \rho U^2 S}{2} \quad (3)$$

So, C_D and C_L can be given as [3];

$$C_D = \frac{2F_D}{\rho U^2 S} \quad (4)$$

$$C_L = \frac{2F_L}{\rho U^2 S} \quad (5)$$

Here, S is the airfoil reference area.

Figure 1 shows the schematic representation of an airfoil with forces around it. In this Figure, α shows the angle of attack.

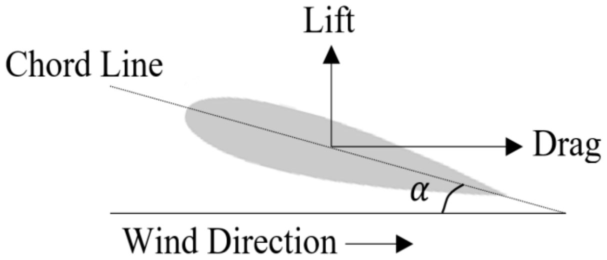

Figure 1. Schematic representation of an airfoil

$$K_t = \frac{\sigma_{emniyet}}{\sigma_{normal}} \quad (1)$$

2.2.Modelling the Airfoils

In the present work, airfoils were modelled in two dimensions. There are four different models created; base model ($M1$), airfoil with a rib structure ($M2$), airfoil with a plain flap ($M3$) and airfoil with a plain flap and rib structure ($M4$). Figure 2 shows created models.

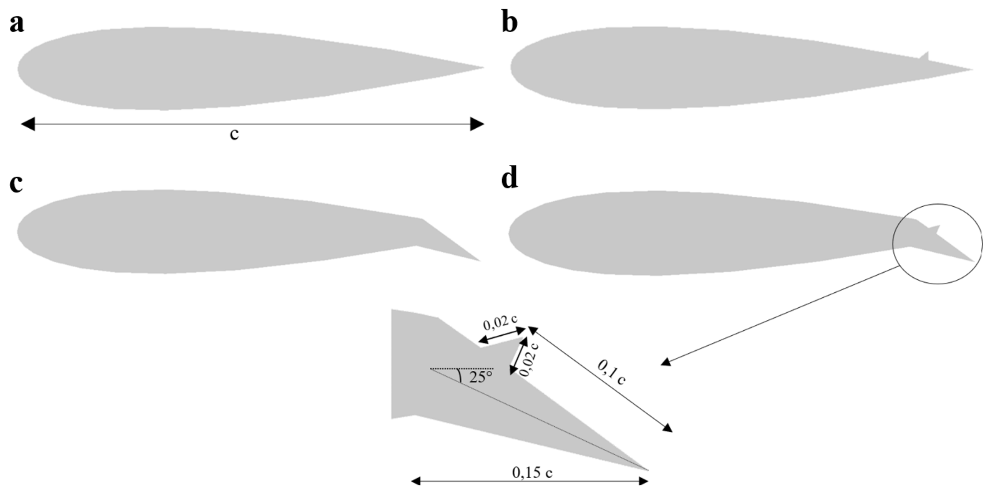

Figure 2. Created Designs a) $M1$ model b) $M2$ model c) $M3$ model d) $M4$ model

The dimensions of the rib structure were taken from Tanürün et al.'s study [7]. A plain flap was created with an angle of 25°. Furthermore, it was designed to be 0,15 c away from the airfoil's trailing edge. These values were selected considering Genç et al.'s research [13]. For all created models, c is equal to 100 mm. It should be noted that for NACA XXXX airfoils, the maximum mean camber is indicated by the first digit and the maximum camber's location is specified by the second digit. The last two digits show the airfoil's maximum thickness. For the NACA 0018 airfoil, since the first two digits are equal to 0, the airfoil has no camber and is a symmetrical airfoil.

2.3.Computational Domain and Mesh Structure

While creating the computational domain, the dimensions must be chosen carefully. Otherwise, the solution will take longer, or the results will be inaccurate.

This is also true for the created mesh structure. Figure 3 shows the created computational domain..

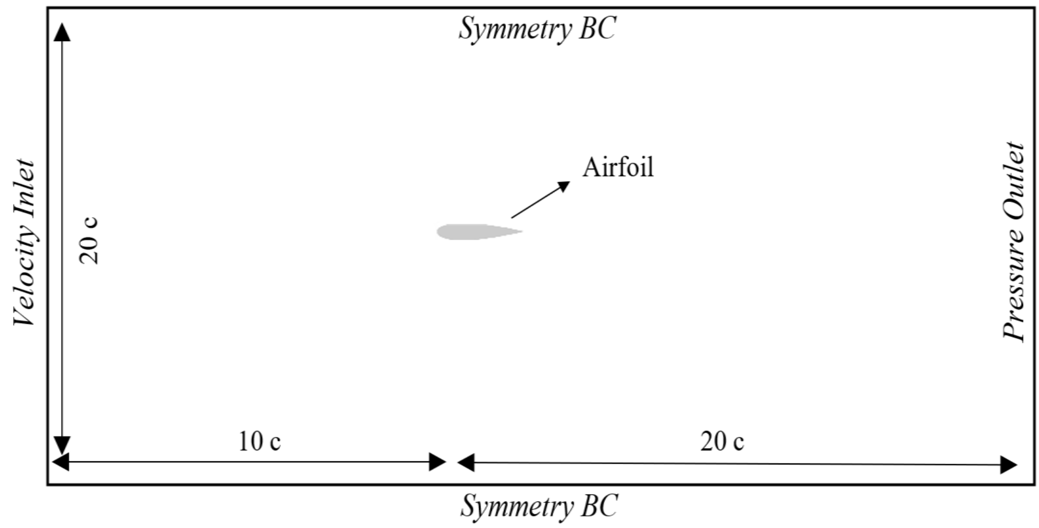

Figure 3. Computational Domain

The distance between the inlet side and the origin was selected as 10 c. The Outlet side is 20 c away from the origin. Symmetry boundary condition was used for both the upper and bottom sides. The distance between the upper and the bottom side is equal to 20 c. While selecting these distances, existing studies from the literature were considered [7,14].

Four different mesh structures were created and C_L and C_D were calculated at an angle of attack of 10° using the Spalart-Allmaras turbulence model to achieve the independence from the mesh structure. Figure 4 shows the calculated C_L and C_D values with respect to the number of mesh elements.

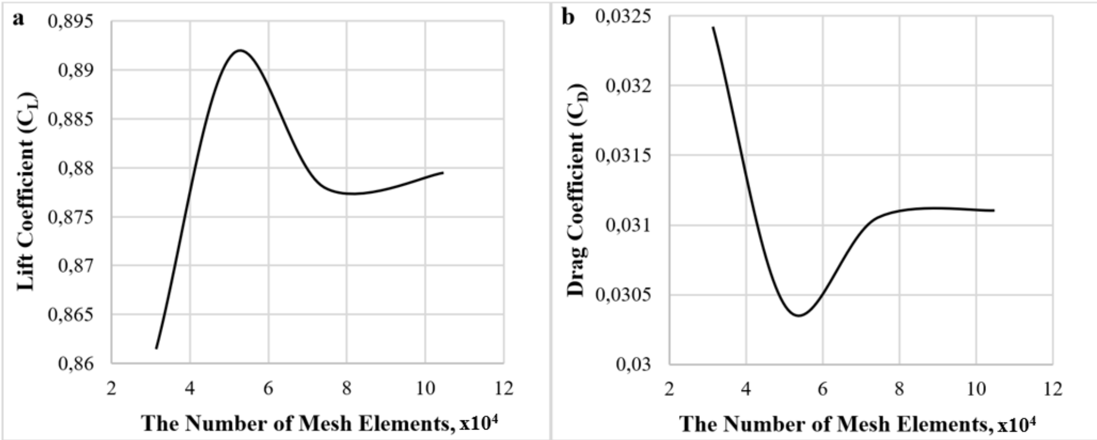

Figure 4. Lift and Drag Coefficients vs. the Number of Mesh Elements

C_L was calculated as 0,878 and 0,879 for the number of mesh elements to be 74272 and 104556, respectively. Moreover, the difference between the calculated C_D values for the number of mesh elements of 74272 and 104556 is 0,165%. Since changes in C_D and C_L values remained very small, the mesh structure with a 74272 number of mesh elements was used for the next steps of this study. Figure 5 shows the created mesh structure. The maximum skewness, average orthogonal quality, and overall element quality values equal 0,735, 0,948, and 0,945, respectively. The mesh growth rate was set to 1,1.

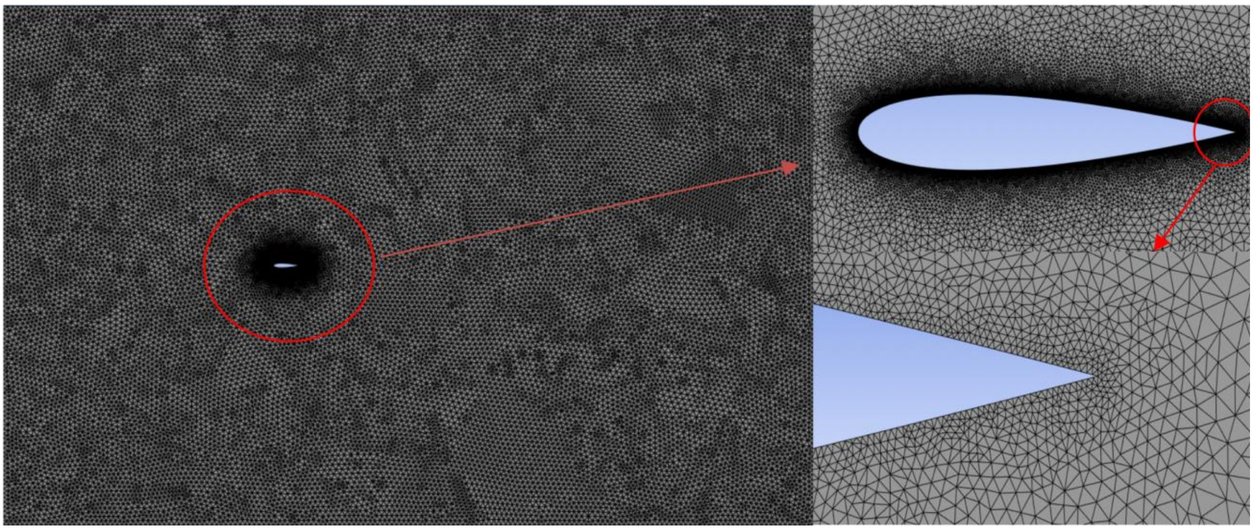

Figure 5. Mesh Structure

2.4. Numerical Settings and Validation Study

The Spalart-Allmaras turbulence model is widely chosen for the numerical analysis of airfoils. Some researchers mentioned that this turbulence model has the highest accuracy [12]. Furthermore, this turbulence model was developed mainly for aerospace applications involving space or aero body parameters, such as an airfoil [15]. Moreover, since the Spalart-Allmaras turbulence model solves only one transport equation, solutions may be completed in the shortest time, compared with other turbulence models. So, in this study, the validation study of experimental results [16] was carried out using the Spalart-Allmaras model. Figure 6 shows the validation of the computational fluid dynamics (CFD) model for the NACA 0018 airfoil.

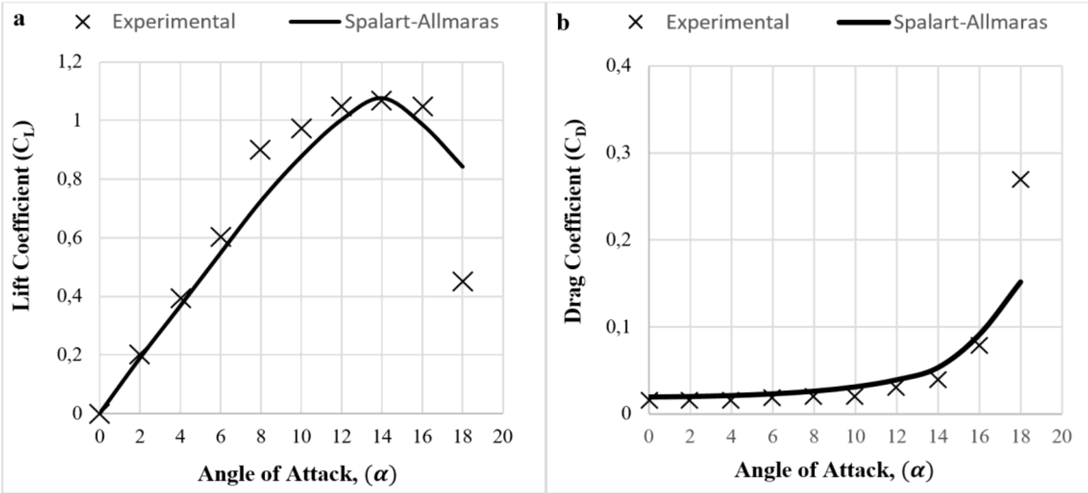

Figure 6. Validation of the Created Model a) Lift oefficient b) Drag Coefficient

Wind enters the computational domain from the velocity inlet side and leaves the domain from the pressure outlet side. Wind velocity was set to 42,5 m/s. At this point, the Re is equal to $3x10^5$. In order to discretize the momentum and modified turbulent viscosity, the second order upwind formulation was selected. Furthermore, the convergence criterion for continuity was set to 10^{-5}.

3. RESULTS

Tanürün et al. [7] investigated the rib effect on the performance of an asymmetrical NACA 2412 airfoil without a flap structure. In the present study, the effect of rib structure on the aerodynamic performance of a symmetrical flapped airfoil was examined numerically. After creating the mesh structure, experimental results [16] for the NACA 0018 airfoil were validated with the Spalart-Allmaras turbulence model.

Figure 6 shows the comparison C_L values of four different airfoil structures, $M1$, $M2$, $M3$ and $M4$ (see in Figure 2) at different (α) values.

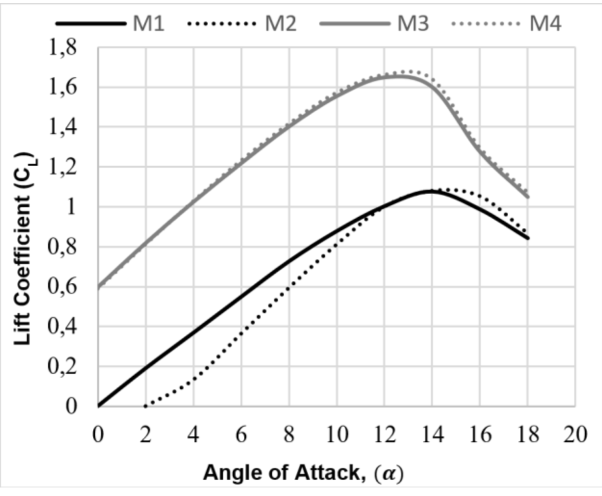

Figure 6. Lift Coefficient (C_L) of created models

As seen in Figure 6, using the rib structure decreased the C_L at the angle of attack between 0° and 12°. When 12° < α < 18°, C_L was increased by using the rib structure. It can be said that the rib structure is effective at lower attack angles. Same trend was also seen by Tanürün et al. [7].

C_L values were increased significantly by using the plain flap. Moreover, using the rib structure with the plain flapped airfoil increased C_L values at almost all attack angles. When the angle of attack is higher than 4°, C_L values of the $M4$ model were determined to be bigger than the C_L values of the $M3$ model. While the rib structure increased C_L values only at higher attack angles for the base airfoil ($M1$ model), it raised C_L values both at high and low attack angles for the plain flapped airfoil ($M3$ model). The maximum C_L values were calculated as 1,077, 1,079, 1,6496 and 1,6606 for $M1$, $M2$, $M3$ and $M4$ models, respectively. Stall angles were determined as 14° for both the $M1$ and $M2$ models and it was calculated as 12° for both the $M3$ and $M4$ models. So, it was observed that using the plain flap decreased the stall angle.

Figure 7 shows changes in C_D values for four different models. When $M1$ and $M2$ models are examined, it can be seen that the rib structure increased C_D values when the attack angle is < 12°. However, at higher attack angles, C_D values were decreased by using the rib structure. Tanürün et al. also found similar results with an asymmetrical airfoil [7].

The plain flap caused a significant rise in C_D values. At all attack angles, higher C_D values were observed with the $M3$ model than they were calculated with the $M1$ model. However, using the rib structure with the plain flapped airfoil decreased C_D values at all α values (see $M3$ and $M4$ models in Figure 7). The maximum C_D values were calculated as 0,1515, 0,1494, 0,3287 and 0,3183 for $M1$, $M2$, $M3$ and $M4$ design, respectively.

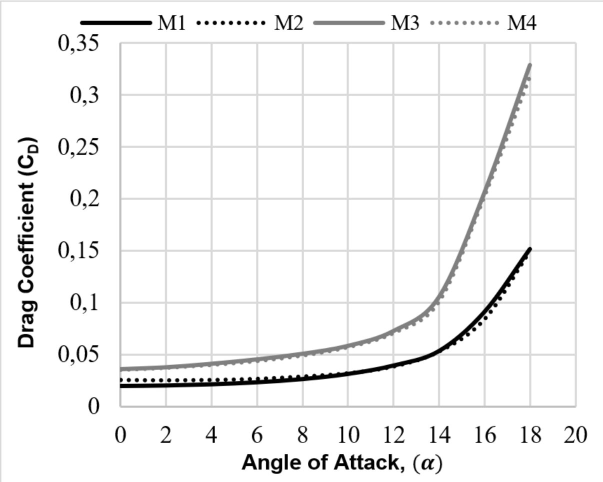

Figure 7. Drag Coefficient (C_D) of created models

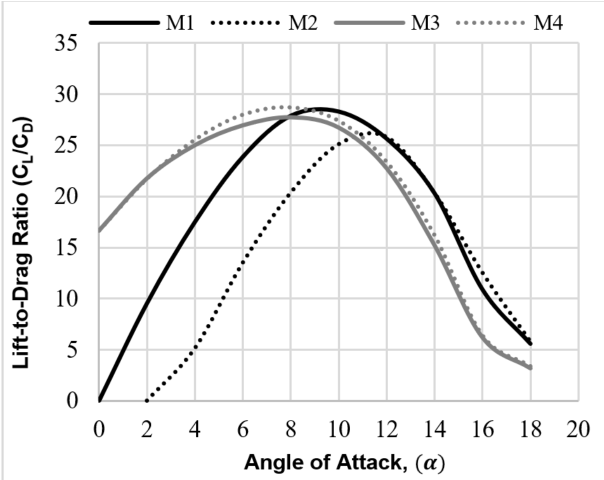

Figure 8. Lift-to-Drag ratios (C_L/C_D) of created models

In the literature, various studies can be found that investigated an airfoil's aerodynamic performance by calculating C_L/C_D ratios [13,17,18]. So, in this study, the aerodynamic characteristics of different models were also examined in terms of the C_L/C_D ratio.

Figure 8 shows calculated C_L/C_D ratios for different models. When comparing $M1$ and $M2$ models, it was observed that using the rib structure increased the aerodynamic performance of the $M1$ model when the α > 12°. However, the aerodynamic performance was declined by using the rib structure at lower α values. Between 0° < α < 8°, C_L/C_D were raised by using the plain flap.

The NACA 0018 airfoil's aerodynamic performance with a plain flap structure worsened at higher α values because the drag coefficient increased noticeably at greater attack angles. A similar trend can be found in Genç et al.'s study [13]. The maximum C_L/C_D ratios were calculated as 28,277, 25,84, 27,7094 and 28,7085 for $M1$, $M2$, $M3$ and $M4$ models, respectively.

Table 1 shows the C_L, C_D and C_L/C_D values at different attack angles for both the $M3$ and $M4$ models. From this table, it should be noticed that using the rib structure with the flapped airfoil increased the aerodynamic performance at almost all attack angles except 0° and 2°, while the rib structure climbed the non-flapped airfoil's aerodynamic performance at only high attack angles

Table 1. Comparing C_L, C_D and C_L/C_D values of $M3$ and $M4$ Design

Angle of Attack (α)	$C_L, M3$	$C_L, M4$	$C_D, M3$	$C_D, M4$	$C_L/C_D, M3$	$C_L/C_D, M4$	**Difference in C_L/C_D**
0°	0,5971	0,5918	0,0358	0,0355	16,6617	16,6493	**-0,0745 %**
2°	0,8179	0,8137	0,0376	0,0375	21,7513	21,7254	**-0,1190 %**
4°	1,0246	1,0287	0,0410	0,0403	24,9854	25,5521	**2,2681 %**
6°	1,2183	1,2321	0,0452	0,0440	26,9255	27,9959	**3,9753 %**
8°	1,4024	1,4157	0,0506	0,0493	27,7094	28,7085	**3,6055 %**
10°	1,5551	1,5715	0,0582	0,0574	26,6993	27,3924	**2,5959 %**
12°	1,6496	1,6606	0,0726	0,0710	22,7261	23,3825	**2,8880 %**
14°	1,6010	1,6385	0,1053	0,1012	15,2042	16,1875	**6,4675 %**
16°	1,2766	1,2939	0,2059	0,2027	6,1998	6,3830	**2,9552 %**
18°	1,0496	1,0716	0,3287	0,3183	3,1932	3,3667	**5,4352 %**

4. SUMMARY AND CONCLUSION

In this study, the performances of four various airfoil models were compared. Two-dimensional numerical analyses were performed using ANSYS Fluent software. It was aimed to examine the effect of a rib structure on the aerodynamic performance of a symmetrical NACA 0018 plain flapped airfoil. The comments are as follows;

- Mesh independency study was carried out. As the difference between calculated C_L and C_D values for the number of mesh elements are 74272 and 104556 calculated very small, the mesh structure that has 74272 mesh elements was used for the present study.
- Validation of the experimental study [16] was carried out using the Spalart-Allmaras turbulence model. Numerical results were calculated very close to experimental results.
- There are four different airfoil models were created. Airfoil without flap and rib ($M1$), airfoil with rib ($M2$), airfoil with plain flap ($M3$) and airfoil with plain flap and rib ($M4$).
- C_L values were increased significantly with using the plain flap. When the attack angle is < 12°, C_L values of the $M1$ model were calculated higher than it was calculated for the $M2$ model. Likewise, when the angle of attack > 12°, rib structure increased C_L values of the $M1$ model. The rib structure increased the C_L of the plain flapped airfoil when α > 2°.
- C_D values were also increased with using the plain flap. Rib structure decreased C_D values of the $M1$ model at α > 12°. Furthermore, it was seen that the rib structure declined C_D values of plain flapped airfoil at all α values.
- C_L/C_D values of plain flapped airfoil ($M3$) and plain flapped airfoil with the rib structure ($M4$) were compared. The rib structure increased the aerodynamic performance of the plain flapped airfoil at α > 2°.

Verifying these results is recommended since the difference between experimental and numerical results is noticeable at higher attack angles.. Similar results were obtained in other studies [19,20]. A three-dimensional study could give more accurate results. However, it should be noted that computational requirements will be higher for three-dimensional simulations. For future studies, the combination of different flap types and rib structures can be examined. The effects of geometric properties of created rib structure and its position on the aerodynamic performance of different types of airfoils may be investigated.

NOMENCLATURE

CFD	Computational Fluid Dynamics
TSR	Tip Speed Ratio
SST	Shear Stress Transport
C_L	Lift Coefficient
C_D	Drag Coefficient
c	Chord Length (m)
Re	Reynolds Number
U	Flow Speed (m/s)
S	Airfoil Surface Area
ρ	Density (kg/m$^{3)}$
F_L	Lift Force
F_D	Drag Force

DECLARATION OF ETHICAL STANDARDS

The author(s) of this article declare that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.

AUTHORS' CONTRIBUTIONS

Ahmet Fatih KAYA: Performed the simulations, analyse the results and wrote the manuscript.

CONFLICT OF INTEREST

There is no conflict of interest in this study.

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