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Evaluating the effect of unsteady air flow on a slotted aerofoil of wind turbines

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ABSTRACT

In this study, three types of aerofoils were examined at various angles of attack and at a steady value then fluctuated of air flow. Then, the findings were compared to the XFOIL prediction results. The experimental and simulation results were consistent to some extent with the XFOIL prediction results. The shape of the chosen aerofoils was modified by making a slot through the blade the aerofoil and studying their effect on the aerodynamics of the modified shape. The slotted aerofoil shape was studied as it faced a fluctuated wind flow. The results revealed that the increase in angles of attack, the lift force increased and approximated its maximum value and then began to decrease with the slot. During the calculations, a case study for the number of elements was done to obtain the best mesh.

The experimental and simulations were conducted by using ANSYS CFD at Reynolds number 10^6 and AOA equals (0°, 4°, 8°, 10°, 12°, 15°, 16°, 17°, 18°) for three shapes of aerofoils which are without a slot, two of which are symmetrical, NACA 0012 and NACA 0015, and one asymmetrical, which is NACA 4415. The slotted aerofoil (existence of an opening after 40% from the leading edge) which is the NACA 0015 aerofoil, was simulated.

Keywords: NACA 0012 and NACA 0015; CFD; Unsteady flow; slotted aerofoil.

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1. Introduction

Recently, modifications in wind turbines blades have become more interesting for researchers and engineers. Many researchers have modified and studied the shape of the wind turbine blades and the influence of these modifications on aerodynamics of wind turbines. Douvi C. Eleni et al [1] evaluated various turbulence models for the flow over the 4-digit symmetric aerofoil NACA 0012 aerofoil. The turbulence model k-ω SST two-equation model showed an acceptable agreement with previous studies. K. Prudhvi et al [2] simulated a NACA 0015 by using CFD at AOA equaled to 0 degree and 6 degrees respectively. It was proved that the lift was still low at low degrees of AOA then the lift force increased when AOA values increased. Obviously, the value of drag force also improved, however, the increment in drag force was still quite lower compared to the lift force value.

İ. Şahin and A. Acir [3] accomplished both experimental and numerical study to test the aerodynamics of the NACA 0015 wind turbine aerofoil. A FLUENT Ansys tool was employed for numerical calculations. The results exhibited that the aerodynamics coefficients raised with the increasing of angles of attack. The separation point was at 16° attack angle. Therefore, the lift coefficient decreased as the drag coefficient increased. Then, the highest lift value was at 16°. Experimental and numerical analyses were revealed good similarities. The researcher used a speed of 10 m/s which was corresponding to Re = 68490.

I. Rubel et al [4] achieved a comparison study of aerodynamics of NACA 0012 and NACA 4415 aerofoil blade. The comparison declared that the NACA 4415 aerofoil had noticeably effective aerodynamic shape. Moreover, the NACA 4415 produced a high lift force due to its shape that could generate a large negative pressure. Furthermore, stall occurred for NACA 0015 at the range $10° < \alpha \leq 15°$ AOA. Moreover, for the numerical study, the mesh size was recommended to be fine to catch even the smallest eddy fluctuations. However, it would consume a lot of power and might be time.

A. Dash [5] performed an analysis of aerodynamic performance of NACA0012 aerofoil. It was conducted at many values of angles of attack and the Reynolds number was (10^6). The velocity of flow at the upper surface was higher than that of the lower surface. So, the pressure of the flow at the above surface of the aerofoil was negative while at the lower surface was positive. The increase in the value of lift force and lift coefficient, the value of the angle of attack increased. Therefore, a rise in the drag force might occur. The CFD analysis was an efficient alternative to experimental methods.

N. A. Ismail, et al [6] directed an experimental research to study the varying of angles of attack on aerodynamics of the wing had NACA 4415 aerofoils. A low-speed wind tunnel was employed at two different Reynolds number. The distribution of the pressure along the span of the wing shape was also computed. In addition, the NACA 4415 shape showed high lift and low drag coefficient. So, the NACA 4415 aerofoil could be used for several wind applications.

M. Premkumar et al [7] studied numerically the cambered aerofoil blade a vertical axis wind turbine blades. The self-starting of the symmetrical NACA 0012 and cambered NACA 4415 blades were studied at various angles of attack. The torque of the turbine with the NACA 0012 aerofoil showed 9% enhancement compared to that of NACA 4415 aerofoil. However, the lift force, for the cambered blade, was high.

More than 5 % increase in aerodynamics efficiency for the NACA 4412 aerofoil with a slot and various angles of attack was concluded by [8,9]. Ni et al [10] conducted both experimental and numerical investigation on a slotted blade. The study found that the flow separation can delaying, and the lift increased 58% at high angles of attack at Re number 1.6×10^6.

The slotted S809 aerofoil was tested experimentally and numerically by Moshfeghi et al [11] with various AOAs (0, 10, 15 and 20) degrees. The separation was clear with high AOAs. H. Yeo, and J.W. Lim [12] the slotted aerofoil enhanced 25% the thrust force of a helicopter even though the high drag force at low AOAs. The slotted aerofoil was utilized by Belamadi et al [13] in wind turbines field. The aerodynamic efficiency of the wind turbine enhanced with the slotted aerofoil than the baseline one. The study of Zhu et al [14] showed that the performance of the flapping aerofoil was enhanced by adding a slotted leading edge on the aerofoil shape. Niyas et al [15] introduced a novel slotted shape of the aerofoil of horizontal axis wind turbines. It was noted that the modified aerofoil can improve the lift force and defer the stall to another angle of attack.

A numerical analysis was conducted by Michael Todorov [16] concluded that the slotted wing had more significant lift force than that from the normal wing. The unsteady wind flow around a symmetric aerofoil was conducted numerically by Kurtulus [17]. It was found that the lift force increased as the wake width increased. In addition, the Reynolds number was 10^6, which was employed by Rohilla et al [18] to study the flow above 12% aerofoil using the k- ω SST model. Therefore, the current research will investigate the effect of fluctuated wind flow (1Hz) on the aerodynamics of a symmetric slotted aerofoil NACA 0015 with a 0.7m chord. The geometry of the current slot is made with a 0.04 m and 32% of the chord of the NACA 0015 aerofoil.

2. Experimental approach

The two models of aerofoils (with and without slot) were placed individually in a wind flow tunnel. The wind tunnel is used for the qualitative demonstration of the wind flow created then sucked through a test section to study the flow around various types of drag bodies. The experimental work was conducted under the steady state flow due to the used wind tunnel has not more facilities to run the unsteady wind flow. So, the CFD will be utilized to run the case of fluctuated wind flow.

3. CFD geometry model

Firstly, the workbench was selected to simulate the fluid flow above the selected 2D geometries. Three types of aerofoil, which are NACA 0012, 0015 and 4415, were employed in the current study, as shown in Figure. 1 a, b, c respectively.

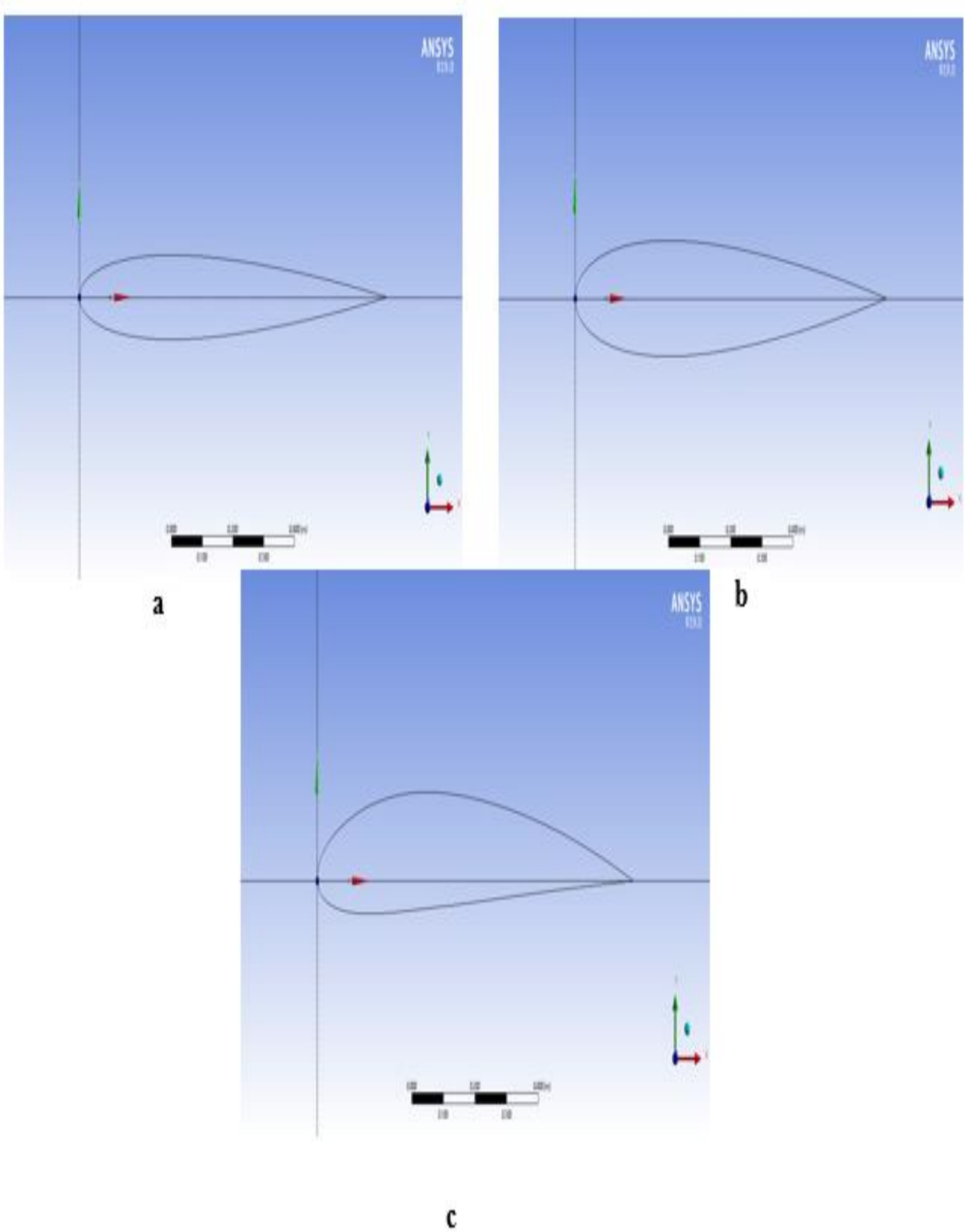

Figure 1. The side view of NACA 0012, NACA 0015 and NACA 4415 respectively

3.1. Mesh of the model

Mesh quality has a major impact on the simulation process and its results, Therefore, it must be suitable, so that the number of elements is not too many, causing problems with performance and time, and the same results can be obtained with fewer elements, and also the number of elements should not be too few, as it does not give good results, Therefore, a case study to the number of mesh element was conducted. The case study was conducted on a NACA 0012 at three different AOA. The structure C-mesh method was used, as shown in Figure 2. The concentrate of the number of elements around the aerofoil boundary is shown in Figure 3. The test started with a small number of elements equal to 21000 grids, and then the number increased gradually.

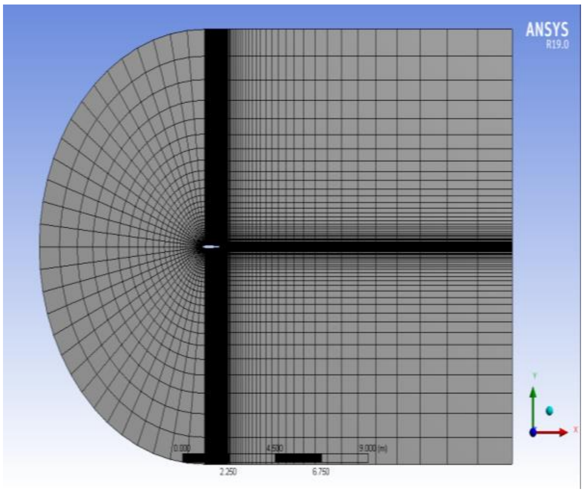

Figure 2. Mesh of the whole domain

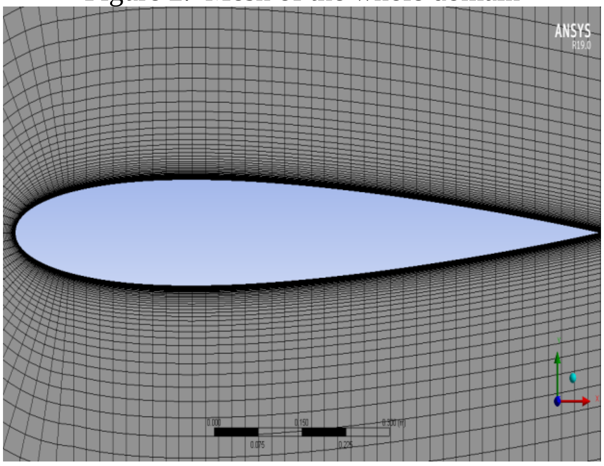

Figure 3. Mesh around aerofoil

3.2. Mesh independence study

The simulation at AOA= 8°, which the number of elements is 21000, was completed. Then, parameters set was utilised to gradually change the number of elements then recorded values of C_L and C_D at each number of elements. The table 1 shows through its data, that the best number of elements was 132500. So, it was used with all the calculations.

Table 1: C_L for each No. of elements at three different AOA

No. of elements	C_L		
	AOA = 8°	AOA = 10°	AOA = 12°
21000	0.80433299	0.96988732	1.0885453
46500	0.81683052	0.99737591	1.1507526
84000	0.82252771	1.0092658	1.1744025
132500	0.82596034	1.0143095	1.1817669
198000	0.82821755	1.0169957	1.1843851
276500	0.82913994	1.0176682	1.1837576
368000	0.82533451	1.0184517	1.1845338

4. Slotted aerofoil geometry

After the analysis of the aerofoils without the slot was completed, a modification in the aerofoil shape was conducted and other analyses of the new aerofoils using NACA 0015 were run. The same as the previous steps except the number of network elements, which was slightly increased because of the slot, as seen Figure 4. The specifications of the slot are seen in Figure 5.

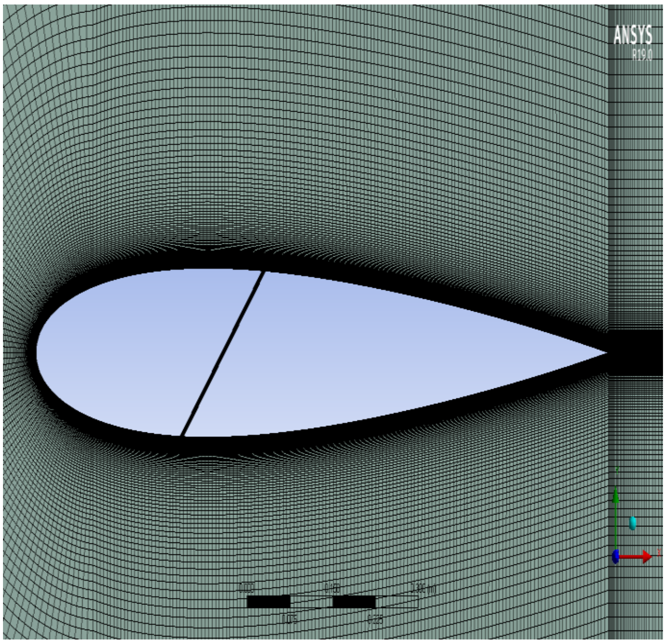

Figure 4. Final mesh around slotted aerofoil

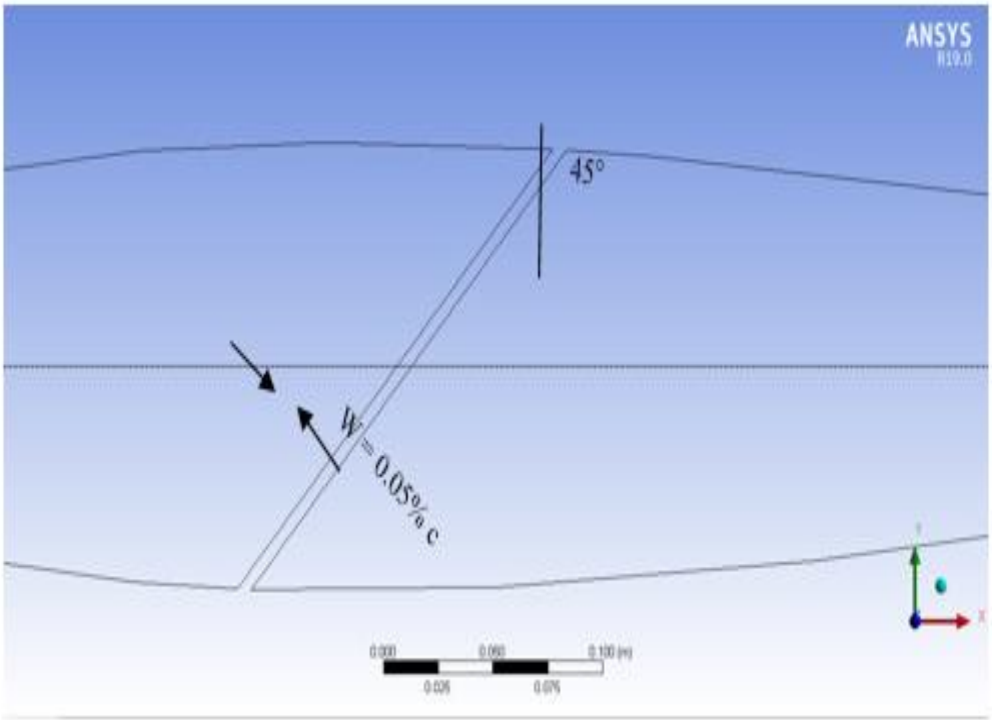

Figure 5. Dimensions of the slot

5. Unsteady wind flow

The average wind flow could be insufficient to obtain high aerodynamics results, so flow changes with time might be better to run the simulations for various NACA shapes. The following mathematics form was applied to compute the instantons wind speed of the current simulations [19]:

$$V = \bar{U} + A \sin(2\pi f) \quad (1)$$

Where $\bar{U}$ represents the mean speed of flow in meter per second, A is wind amplitude in m, and f is the fluctuations of flow in Hz.

6. Results and discussions

The experimental work studies revealed that the slot has an essential effect on the increasing the lift force and delay the stall angle about two degrees, as seen in Figure 6. The slot technique forced the flow to be attached with the surface of the aerofoil. It could enable the flow above the aerofoil to have more momentum.

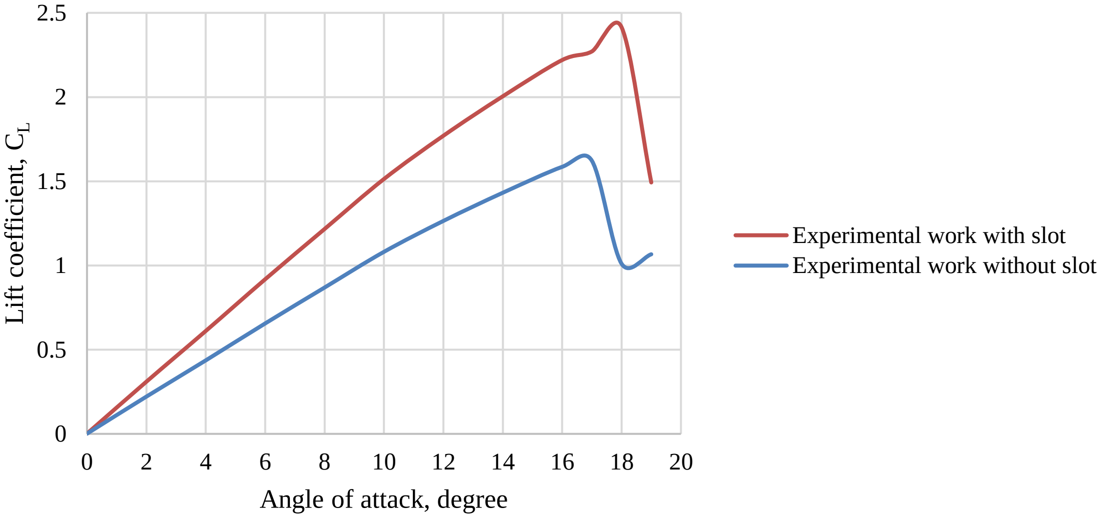

Figure 6. Lift force with the presence of slot at steady wind flow

The following Figure represents the comparison between the current experimental and CFD work.

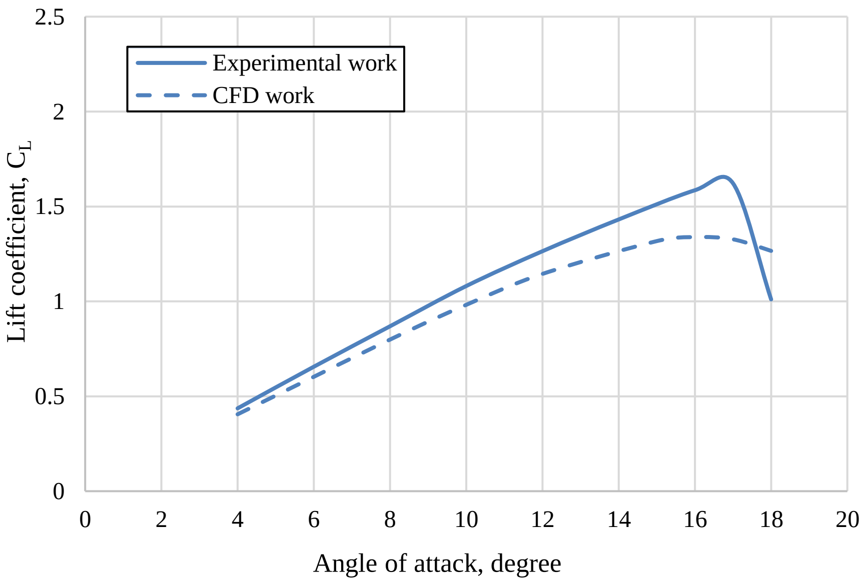

Figure 7. Lift force for experimental and CFD work (without slot) under steady state wind flow

In Figure 7, there is no big difference between the experimental and CFD curves. That means the CFD can be depended when run simulations about the slot cases.

Simulations were performed for three different types of aerofoil at AOA equal (0°, 2°, 4°, 6°, 8°, 10°, 12°, 15°, 16°, 17°, 18°, 19°, 20°), and the results were compared with XFOIL prediction.

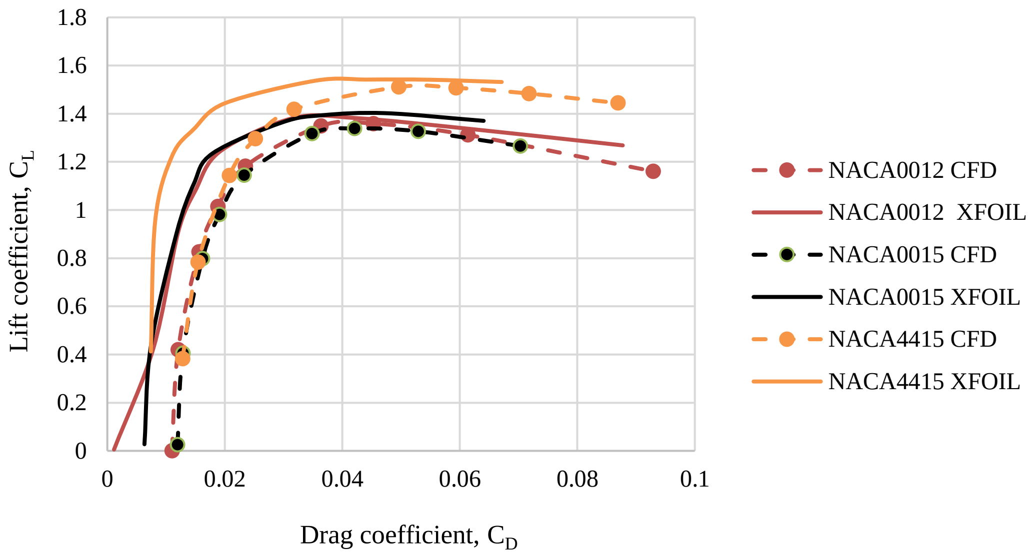

Figure 8: Effect of different NACAs at steady wind flow

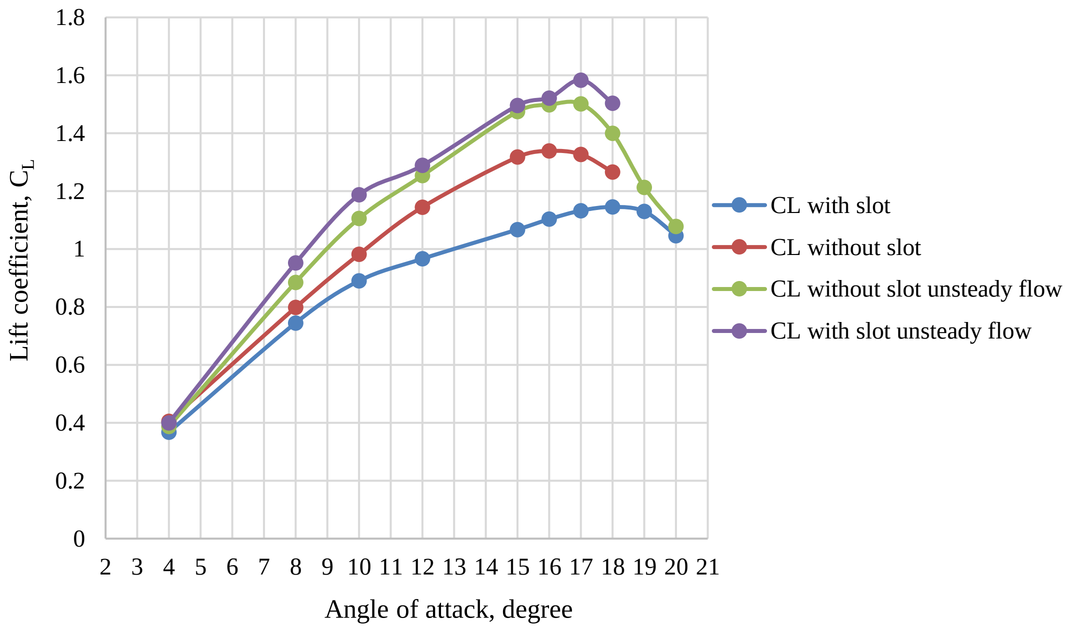

Figure 9. Effect of the slot on the lift force for NACA 0012 at different wind flow

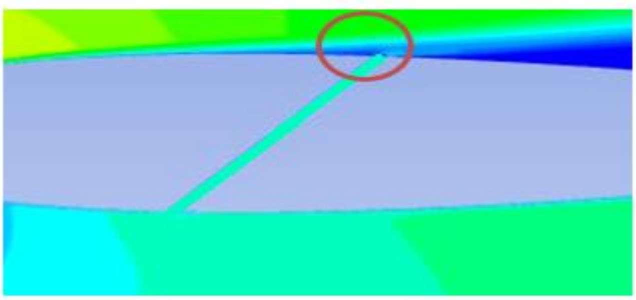

Figure 10. Contour of the slot at 12° and 1Hz

Figures 8, 9 and 10 demonstrate clearly that the lift and drag coefficient values grew with the AOAs. However, at a certain angle, a decrease occurred in the lift coefficient as the flow detached from the upper face of aerofoils.

The lift on NACA 4415 is 1.5109 greater than that of the NACA 0012 which equal 1.3387 and NACA 0015 which equal 1.3387 due to its design. The maximum lift for the NACA 0012 and NACA 0015 at 16^o AOA, while for NACA 4415 at 15^o AOA. As for the drag, it also increased with the increase in the AOA. When the aerofoil is rising, which means the surface area increased so it is countering a large amount of air. After making the modification to the aerofoil, it was noticed a delay in the occurrence of stall, so the stall angle becomes 18^o after it was 16^o. The reason for this delay is that the slot worked to acceleration of the air inside it according to the (Venturi effect), which states that there is a reduction in a flow pressure when it is passing through a constricted section. The contour shows that there is a little flow attach at the suction side of the aerofoil (red cycle). This means that the slot is useful to delay the separation of the flow. Using developed wireless monitoring systems for turbines based on compact antennas and filters and Internet of Thing (IoT) are useful future work of this study [20-24].

7. Conclusions

In the current search, the two-dimensional simulation of three types of aerofoil was run. Lift to drag coefficients were computed for the three types. It was noticed that lift to drag coefficients increased when angles of attack increased, but at a certain limit, the collapse occurs, which is called stall. Additionally, the k-ω SST turbulence model was utilised which provided similar predictions of the XFOIL. This paved the way for the next steps. Moreover, the experimental work showed that the slotted aerfoild can enhance the lift force at steady state wind flow. After completing the analysis of the baseline aerofoil, a modification was made to one of the types, to study its effects. A slot was made which both delayed the stall. Furthermore, it can be concluded that the modified NACA 0012 blade achieved better at the fluctuated flow and at high angles than the base blade. In general, the improvement of the slot can be considered to obtain better results especially at unsteady wind flow cases. Further works might be required to examine aerodynamics of a slotted wind blade at various amplitudes of flow.

Declaration of competing interest

The authors declare that they have no known financial or non-financial competing interests in any material discussed in this paper.

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Nomenclature

A Amplitude of wind flow [m].
AOA Angle of attack [degree].
c Aerofoil chord [m]
C_D Drag force coefficient
CFD Computational Fluid Dynamics
C_L Lift force coefficient
NACA National Advisory Committee for Aeronautics
2D Two dimensional
Re Reynolds Number
Ū Mean wind flow [m/s].
V Wind flow velocity [m/s].
w Slot width [m].
XFOIL Analytic and design program
α Angle of attack [degree].
f Frequency of the wind flow [s^{-1}].

References

[1] Douvi C. Eleni, Tsavalos I. Athanasios and Margaris P. Dionissios, "Evaluation of the turbulence models for the simulation of the flow over a National Advisory Committee for Aeronautics (NACA) 0012 airfoil", *Journal of Mechanical Engineering Research*, vol.4, no.3, pp.100-111, 2012.

[2] K. P. Raj, K. S. Kumar, and S. A. Kumar, "CFD Analysis of Naca 0015 Aerofoil," *Int. J. Appl. or Innov.* Eng. Manag., vol. 7, no. 3, pp. 49-53, 2018.

[3] İ. Şahin and A. Acir, "Numerical and Experimental Investigations of Lift and Drag Performances of NACA 0015 Wind Turbine Aerofoil," *Int. J. Mater. Mech. Manuf.*, vol. 3, no. 1, pp. 22–25, 2015.

[4] R. Islam Rubel, M. Kamal Uddin, M. Zahidul Islam, and M. Rokunuzzaman, "Numerical and Experimental Investigation of Aerodynamics Characteristics of NACA 0015 Aerofoil," *Int. J. Eng. Technol.*, vol. 2, no. 4, pp. 132–141, 2017.

[5] A. Dash, "CFD Analysis ofWind Turbine Aerofoil at Various Angles of Attack," *IOSR J. Mech. Civ. Eng.*, vol. 13, no. 04, pp. 18–24, 2016.

[6] K. M. Usman, M. Bolarinwa Balogun, M. Abdullahi, and F. T. Faru, "Effect of Angle of Attack on Lift, Drag, Pitching Moment and Pressure Distribution of NACA 4415," *Journal of science technology and education* , vol. 8, no.1, pp.31-44, 2020.

[7] T. Micha Premkumar, S. Seralathan, T. Mohan, and N. N. P. Saran Reddy, "Numerical Studies on the Effect of Cambered Aerofoil Blades on Self-Starting of Vertical Axis Wind Turbine Part 1: NACA 0012 and NACA 4415," *Appl. Mech. Mater.*, vol. 787, pp. 250–254, 2015.

[8] S. Beyhaghi, R.S. Amano, "Improvement of Aerodynamic Performance of Cambered Airfoils Using Leading-Edge Slots", *Journal of Energy Resources Technology*, vol. 139, no. 5,pp.1-8, 2017.

[9] S. Beyhaghi, and R.S. Amano, "A parametric study on leading-edge slots used on wind turbine airfoils at various angles of attack", *Journal of Wind Engineering and Industrial Aerodynamics*, vol. 175, Pp. 43–52, 2018.

[10] Z. Ni, M. Dhanak, and T. Su, "Improved performance of a slotted blade using a novel slot design", *Journal ofWind Engineering and Industrial Aerodynamics*, vol. 189, pp. 34–44, 2019.

[11] Y. Xie, J. Chen, H. Qu, G. Xie, D. Zhang, and M. Moshfeghi, "Numerical and experimental investigation on the flow separation control of S809 airfoil with slot", Mathematical Problems in Engineering, 2013.

[12] H. Yeo, and J.W. Lim, "Application of a slotted airfoil for UH-60A helicopter performance", National Aeronautics and Space Administration Moffett Field Ca Ames Research, 2002.

[13] R. Belamadia, A. Djemili, A. Ilinca, R. Mdouki, "Aerodynamic performance analysis of slotted airfoils for application to wind turbine blades", *Journal of Wind Engineering and Industrial Aerodynamics*, vol. 151, Pp. 79–99, 2016.

[14] J. Zhang, Y. Yan, P. Xie, L. Jiang, and J. Zhu, "Effect of leading-edge slot on energy capture performance of semi-active flapping airfoil", *Energy Reports*, vol. 8, pp. 5225–5234, 2022.

[15] H. Bhavsar, S. Roy, and H. Niyas, "Multi-element airfoil conFigureuration for HAWT: A novel slot design for improved aerodynamic performance", *Materials Today: Proceedings*, vol. *72*, 386-393, 2022.

[16] M. Todorov, "Aerodynamic Characteristics of Airfoil with Single Slotted Flap for Light Airplane Wing", *International Conference of Scientific Paper*, pp.509-514, 2015.

[17] D. Kurtulus, "On the Unsteady Behavior of theFlow Around NACA 0012 Airfoilwith Steady External Conditionsat Re=1000", *International Journal of Micro Air Vehicles*, vol. 7, pp. 301–326, 2015.

[18] N. Kumar, S. Upadhaya, and A. Rohilla, "Evaluation of the Turbulence Models for the Simulation of the Flow Over a Tsentralniy Aerogidrodinamicheskey institut (TsAGI)-12% Airfoil", *SSRG International Journal of Mechanical Engineering (SSRG - IJME)*, Vol. 4, no. 1, pp. 18–28, 2017

[19] B. A. R. Al-Bakri and R. M. Aljuhashy, "The Aerodynamics of the Wavy Blade under the Effect of Fluctuated Wind Flow", *FME Transactions*, vol.49, no.3, pp.704–710, 2021.

[20] Y. S. Mezaal, H. T. Eyyuboglu, and J. K. Ali, "A novel design of two loosely coupled bandpass filters based on Hilbert-zz resonator with higher harmonic suppression," in *2013 Third International Conference on Advanced Computing and Communication Technologies (ACCT)*, 2013.

[21] S. A. Shandal, Y. S. Mezaal, M. F. Mosleh, and M. A. Kadim, "Miniaturized wideband microstrip antenna for recent wireless applications," *Adv. Electromagn.*, vol. 7, no. 5, pp. 7–13, 2018.

[22] Y. S. Mezaal and H. T. Eyyuboglu, "A new narrow band dual-mode microstrip slotted patch bandpass filter design based on fractal geometry," in *7th International Conference on Computing and Convergence Technology (ICCIT, ICEI and ICACT)*, 2012, pp. 1180–1184.

[23] Y. S. Mezaal, H. H. Saleh, and H. Al-saedi, "New compact microstrip filters based on quasi fractal resonator," *Adv. Electromagn.*, vol. 7, no. 4, pp. 93–102, 2018.

[24] F. Abayaje, S. A. Hashem, H. S. Obaid, Y. S. Mezaal, and S. K. Khaleel, "A miniaturization of the UWB monopole antenna for wireless baseband transmission," *Periodicals of Engineering and Natural Sciences*, vol. 8, no. 1, pp. 256–262, 2020.