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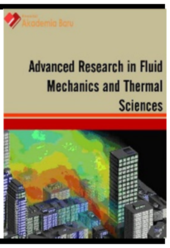

Wind Tunnel Study of the Effect Zigzag Tape on Aerodynamics Performance of A Wind Turbine Airfoil

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ABSTRACT

A wind tunnel study was performed on the FFA-W-3-270 airfoil, which form a segment of a 1.25 MW wind turbine blade, to examine the effect of fixed roughness height and position using a zigzag tape boundary layer trip strip. Tests were conducted at a Reynolds number of 1×10^6 over a wide range of angles of attack. The zigzag tape, as an artificial roughness device, not only triggers a premature transition in the flow whereby laminar flow regimes change to turbulent, but also increases the momentum thickness of the turbulent boundary layer and change the airfoil camber. The 60^o zigzag tape of 0.5 mm and 1 mm height was placed on the suction side of the airfoil at different chord wise locations. The result indicated that the thicker and the closer the tape to the leading edge had more influence on the boundary layer. Due to a drop in the flow velocity at the tape, the static pressure increased. Consequently, the tripped airfoil developed a lower pressure on the suction side in comparison to the clean airfoil. The maximum lift coefficient decreased by up to 31.5% for the 1 mm tape height located at 5% of the chord and the stall occurs at a lower angle of attack.

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1. Introduction

Airfoils employed in a wind turbine blade have a significant influence on the rate of power produced. The airfoil characteristics are influenced by physical and environmental factors, such as contaminants (including sand and grit) deposited by the wind, the ice glaze formation on the leading edge of airfoil in cold climate, the creation of irregularity due to collision of insects, or corrosion by the rain. Subsequently these events can influence the profile, shape and the camber of the airfoil and as a consequence, the aerodynamic characteristics, pressure distribution, and flow pattern of the airfoil are considerably altered. Although the contamination and the increase in roughness to the blade leading edge is inevitable, efforts are required to minimize its effects, due to its influence on aerodynamic performance. In addition, the rated and maximum power generated by rotor can also be reduced, hence airfoils with the least sensitivity to above-mentioned

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parameters are of particular importance. In addition, the presence of contaminants on the blade's trailing edge occurs at double or multiple stall levels which give rise to noise. This results in the premature transition of the laminar boundary layer thereby altering the aerodynamic coefficients.

The zigzag tape is typically used to artificially trigger transition at a fixed position during wind tunnel studies to achieve the same aerodynamic characteristics of the airfoil model as the prototype. The performance of airfoils at subsonic flow conditions can be affected by the laminar separation bubbles whereby the drag will increase on some airfoils. The zigzag tape can also be used to improve the airfoil performance and mitigate the unfavourable effect of bubble drag at low Reynolds numbers. The presence of the tape excites the flow and propagates disturbances in the flow field that enhance the instability of the Tollmien Schlichting waves. In addition, this can trigger a transition of laminar to turbulence flow. An effective tape will also give rise to an increase in the momentum thickness of the turbulent boundary layer that reduces the maximum lift. In addition, the additional drag due to the tape changes pressure through a reduction in the size of the laminar separation bubbles size and an increase frictional drag in the boundary layer. Furthermore, the addition of the zig-zag tape increases the static pressure due to a decrease in the flow velocity.

The height and amount of roughness play a vital role in the fixing transition. Braslow *et al.*, [1] proposed the relation, $12K/Re_{eft}$, to estimate the trip strip roughness height (h). The term Re_{eft} is the Reynolds number per foot based on the free stream speed and distance of the trip strip location from the leading edge and K is a constant. In other words, K is a roughness Reynolds number based on roughness height and should be at least 600 for transition. Selig *et al.*, [2] examined the effect of zigzag tape roughness thickness and tape location on the performance of two specific airfoils in 2D for sailplane applications. Lyon *et al.*, [3] investigated the effect of trip strip on drag variation and laminar separation bubble size using several types of boundary layer trips placed at different locations with different thicknesses for the desired airfoils. Timmer *et al.*, [4,5] performed wind tunnel tests on DU type airfoils namely DU97W300, DU95W180, DU93W210 and DU91W2-250 in wind turbine application. This was performed to achieve the pressure coefficient distributions and aerodynamic characteristics in fixed transition point and free transition conditions using zig-zag tape. Elsinga *et al.,* [6] used PIV measurement to assess the flow pattern behind zigzag tape. The authors concluded that after adding the zigzag tape, the vortices break up into distinct arches producing hairpin structures in the flow field, which are typical of wall-bounded turbulence flow. Schaffarczyk *et al.*, [7] measured the zigzag tape influence on airfoil performance in a 2D wind tunnel test. The authors observed a significant drop in the maximum lift and CL/CD ratio compared to free transition results. Zhang *et al.*, [8] examined the influence of zigzag tape on the aerodynamic performance of a MEXICO rotor. The authors discovered that the zigzag tape changes the boundary layer displacement thickness and decambers the airfoil. The results are a change in the maximum lift and the power coefficients. Fuglsang *et al.*, [9] examined the effect of zigzag tape on FFA-W3-241, FFA-W3-301and NACA 63-430. The authors used 60^{o} and 90^{o} zigzag tapes located at two positions of 5%C and 10%C on the airfoil surfaces. The results revealed that the roughness of the leading edge reduces the suction peak thereby cause a reduction of the maximum lift. Similarly, Gomez *et al.*, [10] investigated the effect of zigzag tape trip strips on the aerodynamic characteristics of the NREL Phase VI rotor. The authors used the zig-zag tape to fix the transition and compared the results to clean or free transition conditions. The results indicated that the thrust and torque values for the clean case are reduced in tripped conditions. Soltani *et al.*, [11] investigated the effect of surface contamination and zigzag tape on lift coefficient on an airfoil in wind turbine applications. The authors placed the zigzag roughness strip at 5%C of the airfoil and demonstrated that the zigzag strip reduces the maximum lift coefficient by up to 35% compared to the clean airfoil. In addition, the stall event occurred at a lower angle of attack during the study.

Hansen *et al.*, [12] have studied the effect of the accumulated inspect, fog and containment on the leading edge of wind turbine blade and they observed that the produced power can be reduced by up to 40% in comparison to clean airfoil.

It is the aim of this study to assess the effect artificial roughness due to the zigzag tape height and chord wise location on the aerodynamics performance of FFA-W3-270 airfoil.

2. Experimental Setup

This study was performed using the Low-Speed Wind Tunnel (a closed circuit, return-type subsonic wind tunnel) located at the Universiti Teknologi Malaysia. The rectangular test section of the low-speed wind tunnel has a cross-sectional volume of 17.4 m3 (2.0 m × 1.5 m × 5.8 m) with a maximum wind speed of 80 m/s powered by a 430 kW AC motor. The flow uniformity and turbulence intensities are about 0.15% and 0.06% respectively. The tests were conducted using a Flygtekniska Forsoks Anstalten model (FFA-W3-270) of the Aeronautical Research Institute of Sweden [13, 14]. The airfoil model was made from fibreglass of 500 mm chord length and 750 mm spanwise length that was installed vertically inside the wind tunnel test section. In order to ensure the correctness of the built airfoil shape, its profile was checked using coordinate measuring machine (CMM). Figure 1 presents a comparison of the true airfoil profile and measured profile by CMM. For the purpose of the simulation of roughness in this study, an experimental study with a 60o zigzag tape of different thickness was fixed on the airfoil surface. Figure 1 shows the installed airfoil with the zig-zag tape strip on the suction side of the airfoil, mounted vertically inside the UTM-LST test section. Two end plates were placed at the span-wise end of the airfoil to eliminate 3D effects and tips vortices.

The JR3-160M50 six-component mounted on an under floor turntable and support system was used to measure the aerodynamic loads and moments. The JR3-160M50 was used due to its high accuracy of measurement with only 0.04% error of the maximum load of the balance, and a suitable load capacity of 3.15 KN for the axial and normal direction of the thick airfoil. The wind tunnel is also equipped with an under floor six-component external balance with lower load capacity suitable for smaller model [15]. The airfoil surfaces were fitted with 30 static pressure taps, 18 taps on the upper surface and 12 taps on the lower surface as tabulated in Table 1. The gap between the pressure taps is directly proportional to the envisaged pressure distribution, so the distance of pressure taps from leading edge increases as flow marches towards the trailing edge. The pressure distribution was recorded through an FKPS 30DP electronic pressure transducer with an accuracy of ±1 psi.

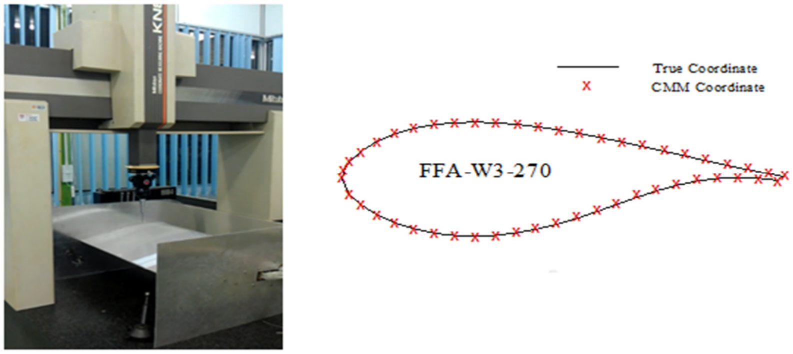


Fig. 1. Comparison of the true airfoil profile and measured profile by CMM

Table 1
Pressure taps locations from the leading edge

Pressure tap No.	Location (mm)	Pressure tap No.	Location (mm)	Pressure tap No.	Location (mm)
1	0.005	11	0.193	21	0.27
2	0.01	12	0.236	22	0.21
3	0.015	13	0.279	23	0.125
4	0.025	14	0.321	24	0.1
5	0.033	15	0.364	25	0.075
6	0.042	16	0.407	26	0.042
7	0.070	17	0.475	27	0.033
8	0.090	18	0.475	28	0.017
9	0.11	19	0.39	29	0.008
10	0.13	20	0.33	30	Stag. point

The tests were performed to obtain aerodynamic loads and pressure coefficient distribution at a Reynolds number of 1×10^6 in a range of angle of attacks (AOA) from -30^o to $+30^o$. The pressure coefficient (Cp), lift coefficient (C_L), drag coefficient (C_D) and pitching moment coefficient (C_M) were calculated respectively as follows: $C_P = (P - P\infty)/(0.5\rho {U_\infty}^2)$, $C_L = L/(0.5\rho\, U_\infty^2)$, $C_D = D/(0.5\rho {U_\infty}^2 C)$ and $C_M = M/(0.5\rho {U_\infty}^2 C^2)$, where ρ is the air density, C the airfoil chord length, P the mean static pressure, p_∞ the free stream static pressure, U_∞ the free stream velocity, L the lift force, D the pressure drag force and M the leading edge pitching moment. The experimental results of the taped airfoil were compared to the data of the clean airfoil that was tested earlier.

In this study, wind tunnel tests were conducted to simulate the roughness effect on the aerodynamic characteristics of a wind turbine airfoil. The FFA-W3-270 is a thick airfoil and can be located at the root segment of a wind turbine rotor blade. In order to simulate the roughness effect in this study, the zigzag tape as a roughness element was mounted at different locations on the upper or suction surfaces of the airfoil. The suction surface has a significant effect on the maximum lift capacity. A suitable tape will trigger a transition from a laminar to turbulent boundary layer on the model at the fixed point. If the zigzag tape protrudes too high above the surface or produced excessive roughness, it can have effects other than just fixing the transition location.

Figure 2 also demonstrates the 60^o zigzag tape with a height of 0.5 mm ($t_{tape}/C=0.001$) and 1 mm ($t_{tape}/C=0.002$) and the tape width is equal to 12 mm. The tape was mounted at different chord wise locations of 5%C, 10%C, 20%C and 40%C on the upper surface of the airfoil.

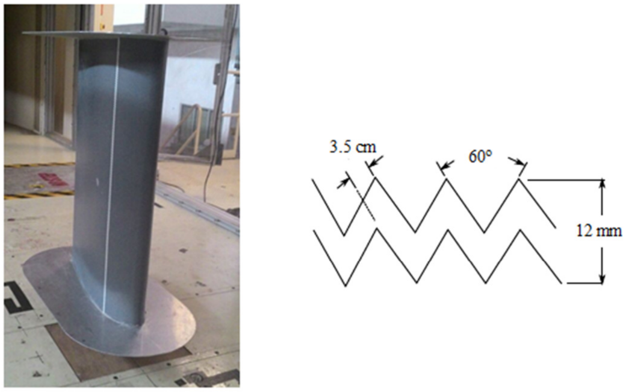
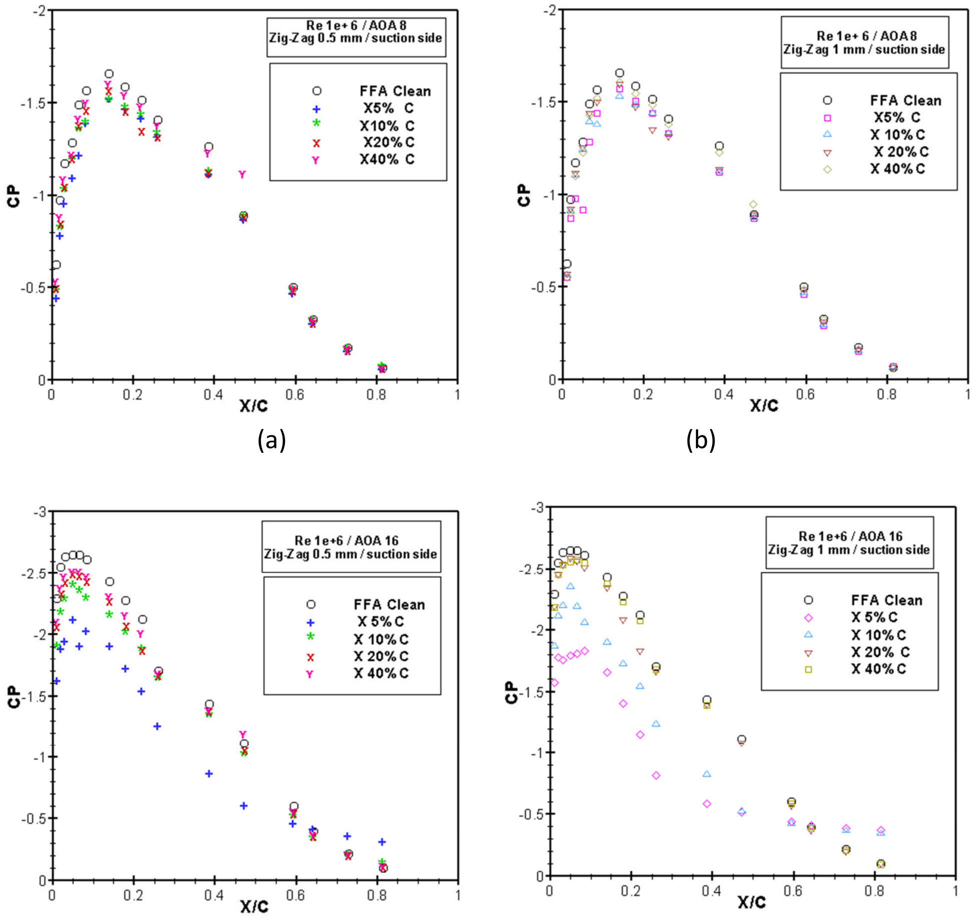


Fig. 2. The zigzag tape as mounted on the FFA-W3-270 airfoil and its dimensions

3. Experimental Results and Discussion

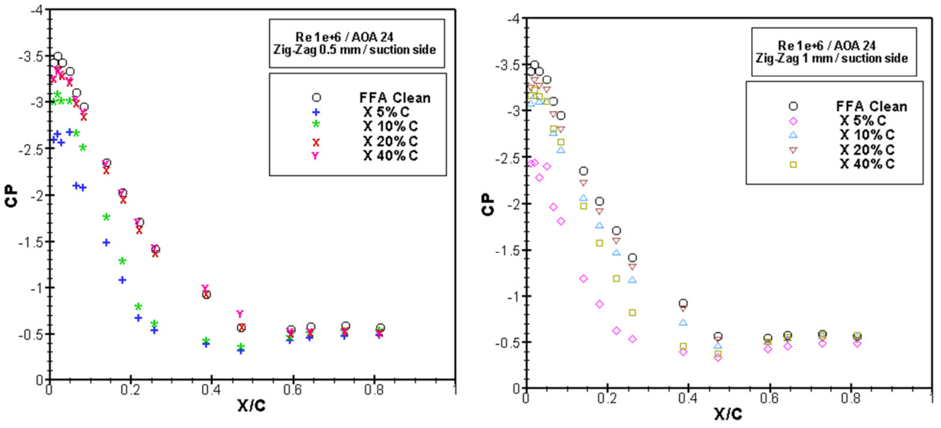
3.1 Pressure Coefficient

The variations of pressure distribution for the tape of two different heights (0.5 mm and 1 mm) and located at different positions (5% C, 10% C, 20% C, and 40% C) on the suction side of the airfoil are presented in Figure 3 (a-f). The results for the taped airfoil were compared to the clean airfoil flow measurement at different AOA at *Re* = 1×10^6. The results show that the higher and closer the location of the tape to the leading edge, the more significant the impact on the pressure distribution. In addition, the pressure distribution curve was further affected by the higher AOA. It can be seen from Figure 3f, which at 24° AOA, the suction pressure coefficient for the clean airfoil of -3.5 reduced to about -2.7 for a taped airfoil with a 0.5 mm height located at 5%C indicating a 28% lost of suction pressure. Similarly, it decreased to about -2.4 for the trip tape with 1 mm height at the same location. It is thus evident that higher suction pressure is achieved with the clean airfoil configuration.



(a) (b)

(c) (d)

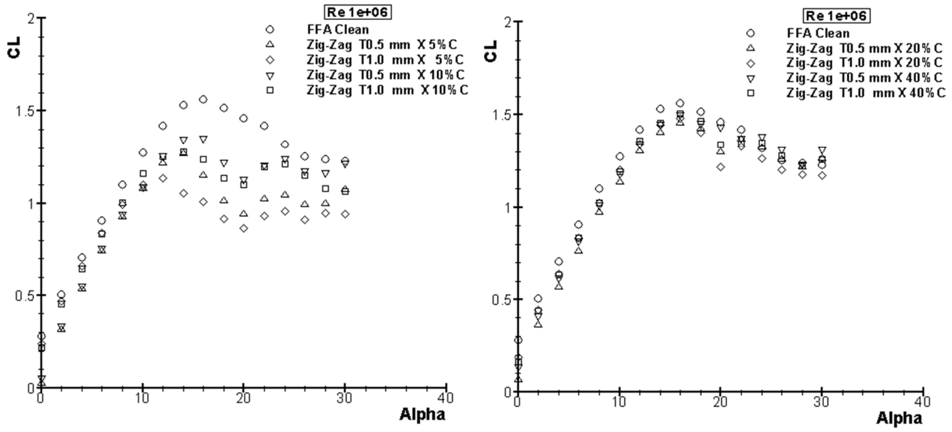


(e) (f)

Fig. 3. Comparison of pressure coefficients between clean and taped airfoil at Re=1×10^6

3.2 Aerodynamics Coefficients

Figure 4 (a-b) illustrates the lift coefficient curves for the taped airfoil. All data were acquired at Re = 1 × 10^6 for a range of AOA from 0^o to 30^o. The results indicate that, the presence of zigzag tape roughness caused the stall to occur at a lower AOA due to a premature separation. In addition, the zig-zag tape played a significant role in reducing the lift force in specific flow regimes i.e. for AOA = 10^o - 30^o. The tape with a 1 mm roughness height placed at 5%C exhibited a significant impact on the maximum lift reduction. In principle, the effect of roughness on the maximum lift decreases by either reducing the roughness height or increasing the roughness distance from the leading edge. However, the trip tape does not only reduce the maximum lift but also stalls the separation of resulting premature flow. According to Figure 4 (a), it is evident that the smooth airfoil maximum lift coefficient (1.6) decreased to 1.1 for a taped airfoil with 1 mm height located at 5%C from the leading edge. This indicated a 31.5% decrease. In addition, the stall angle reduced to 12° while stall occurred at 16° for the clean airfoil.



(a) (b)

Fig. 4. Comparison of lift coefficients between clean and taped airfoil at Re=1×10^6

Figure 5 shows the variation in drag coefficient for taped and clean airfoils at Re = 1×10^6. It can be seen that the drag coefficient for the airfoil with zig-zag tape decreased significantly compared to the clean airfoil. Hence, it is evident that at lower AOAs the difference of the drag coefficients curve between clean and taped airfoil are insignificant. However, the increase in AOA, the two curves gradually shifted apart as the drag coefficient of C_D = 0.17 for clean airfoil decreased to C_D =0.1 for the taped airfoil with 1 mm zigzag height placed at 5%C at 16° AOA. This indicates an almost 41% decrease.

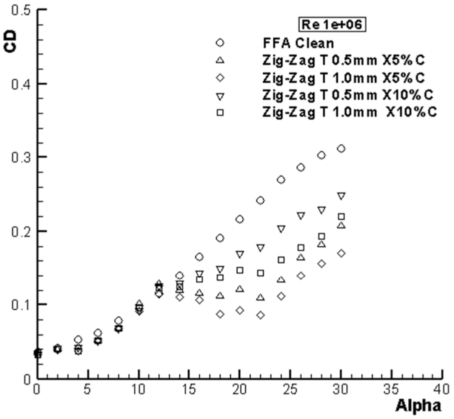
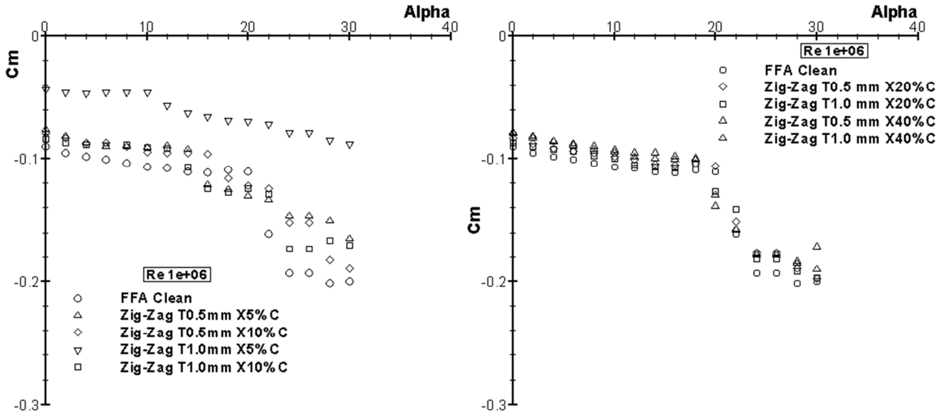


Fig. 5. Comparison of drag coefficients between clean and taped airfoil at Re=1×10^6

Figure 6 (a-b) demonstrates the pitching moment curve for a taped airfoil in comparison to the clean one. As observed, the installation of zigzag tape with 1 mm height located at 5%C has the most significant influence on pitch moment variation in comparison. Hence, it is evident that at zero angle of attack, the C_m coefficient (-0.09) for the clean airfoil approaches -0.04 when the 1 mm height tape is placed at 5%C from the leading edge indicating a 55% increase.



(a) (b)

Fig. 6. Comparison of pitching moment coefficients between clean and taped airfoil at Re=1×10^6

4. Conclusion

This wind tunnel study investigated the aerodynamic characteristics of the FFA-W3-270 airfoil with the 60^o zigzag tape of 0.5 mm and 1 mm height, placed at different chord wise locations on the suction side of the airfoil. The experimental results for taped and clean airfoils were compared at a

Reynolds number of 1×10^6 and angle of attack from 0^o to 30^o. The conclusion can be summarized as follows:

I) The zigzag tape causes a decrease in the maximum lift coefficient of the FFA-W3-270 airfoil. The maximum lift coefficient difference between clean and tripped airfoil are about 31.5% for 1 mm tape thickness located at 5%C

ii) The stall occur at a lower angle of attack of the airfoil, the stall angle for taped airfoil reduced to 12° from 16° for clean airfoil.

iii) The zigzag tape causes a significant reduction in pressure coefficient. At an AOA of 24^o, the large suction peak coefficient for a clean airfoil of -3.5 reduced to -2.5 for a taped airfoil with 1 mm zigzag tape at 5%C, which shows a 28.5% decrease. So the airfoil with zigzag tape experienced a lower pressure on the suction side compared to the clean airfoil. Although the zigzag tape confers additional drag to the total drag, it reduces the pressure drag due to a reduction in the laminar separation bubble size and decreases the skin friction drag.

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