Revista de Ingeniería
ISSN: 0121-4993
reingeri@uniandes.edu.co
Universidad de Los Andes
Colombia

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Revista de Ingeniería, núm. 33, enero-junio, 2011, pp. 14-24
Universidad de Los Andes
Bogotá, Colombia

CFD Analysis of Blunt Trailing Edge Airfoils Obtained with Several Modification Methods

Análisis computacional de perfiles alares con borde de cola recortados con diversos métodos de modificación

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PALABRAS CLAVES

Dinámica de fluido computacional, perfiles modificados, aerodinámica, diseño de turbinas eólicas.

RESUMEN

La modificación de perfiles aerodinámicos para generar bordes de salida con espesor ha probado que es posible obtener buen rendimiento aerodinámico sin comprometer los requerimientos estructurales. Dos diferentes métodos son analizados: el método de recorte y el método de adición de espesor. Simulaciones bidimensionales fueron realizadas usando Ansys CFX® para valores del número de Reynolds de 3.2 millones. Se presenta un estudio basado en los métodos de Taguchi de la familia de perfiles NACA de cuatro dígitos bajo distintos métodos de modificación. Finalmente, un estudio detallado de la modificación del perfil NACA 4421 para distintos espesores de borde de salida es presentado. Los resultados obtenidos muestran que el aumento del coeficiente máximo de sustentación, del ángulo crítico de ataque y del coeficiente de arrastre es común a todos los métodos de modificación, mientras que se probó que en el método de recorte se produce una disminución de la curva de coeficiente de sustentación debida a las alteraciones geométricas causadas. En general, el método de adición de espesor produce perfiles con mayores aumentos en el coeficiente máximo de sustentación y en el ángulo crítico de ataque.

KEY WORDS

CFD, airfoil modification, aerodynamics, wind turbine design.

ABSTRACT

Blunt trailing edge airfoil modification methods have shown that a compromise between aerodynamic performance and structural benefits can be achieved. Two modification methods are studied: the cutting off method and the added thickness method. Two-dimensional simulations were obtained in Ansys CFX® for a typical Reynolds number of 3.2 million. A Taguchi Method experiment is conducted for the study of the four-digit NACA airfoil family with the proposed modification methods. A detailed study for the NACA 4421 modified with several trailing edge thickness values was completed. The results obtained show that the increase in the maximum lift coefficient, the delayed stall and the drag coefficient increase are common to all modification methods studied, whereas it is proven that for the cutting off method the lift coefficient curve displacement to higher angles of attack is caused by the loss of camber. Finally, it was proved that the added thickness method produces larger maximum lift coefficients and larger critical angles of attack than the cutting off method.

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INTRODUCTION

Nowadays wind energy is one of the fastest growing technologies in the energy sector and it is expected to supply 12% of the world's electricity consumption by 2020 [1]. Larger wind turbines with increasing output power are being built every day. Although, technical and/or economical limits to wind turbine size have been predicted in the past, wind turbine growth rates have shown that there seems to be no point where the size would be limited by cost energy constraints [2]. This occurs despite the square-cube law that states that the output power is proportional to the square of the rotor diameter, whereas rotor mass (hence rotor cost) is proportional to the cube of the rotor diameter. As wind turbines keep growing the design loads become larger, introducing structural restrictions at the root region of the blade. In order to fulfill these restrictions it is a common practice to use thick airfoils (airfoil thickness to chord ratio: $t/c > 0.25$) and even circular section geometries. The aerodynamic requirements at these blade positions are obtaining higher maximum lift coefficients at higher angles of attack [3]. The main problem is that these geometries tend to have a rather low aerodynamic performance. There have been several proposals to modify the airfoil geometry in order to fulfill the aerodynamic requirements along with obtaining a larger sectional moment of inertia and a larger area.

Several research studies have shown that blunt trailing edge (flatback) airfoils have a larger moment of inertia and manufacture facilities, in addition to an aerodynamic performance as good as the one shown by the use of common airfoils [4-15]. Two main methods of airfoil modification to obtain blunt trailing edge have been studied by several authors. The first one was introduced in the mid 1950's by NACA(1). The method consists in cutting off a segment from the rear portion of the baseline airfoil. The main problem is that the modified airfoil has a larger airfoil thickness and a smaller camber per chord length. These two parameters play a key role in the aerodynamic performance of an airfoil, and therefore, make it difficult to distinguish their effects on the trailing edge thickness airfoil.

From the NACA contribution to this topic, two papers stand out: Smith and Schaefer [4] with an experimental research of the effects of truncating a NACA 0012 under a Reynolds number of 5 million, and Summers and Page [5] with a study of circular arc airfoils with cut trailing edge under Mach numbers from 0.3 to 0.9. In the 1980's the work carried out by Hoerner and Borst [6], Ramjee et al [7] and Law et al [8] continued using the "truncating" method as well as the work by Timmer [9], Stanway et al [10] and Sato et al [11] done in the 1990's.

Recently, a second method of modification has been proposed by Standish and van Dam [12]. The airfoil modification method consists of symmetrically adding thickness to an airfoil in such a way that the "nose" geometry, airfoil thickness and camber remain the same, but obtaining a blunt trailing edge. This method has been used in other researches such as: Jackson et al [13], Baker et al [14] and Winnermöller et al [15]; all of them were completed under the supervision of Prof. van Dam at the University of California, UC Davis.

This paper presents a computational analysis of the current blunt trailing edge modification methods. A signal to noise ratio study based on Taguchi methods [16] is presented to show the main effect on aerodynamic performance of the different trailing edge thicknesses under different modification methods, as well as to give an idea about the opposite effects between camber, airfoil thickness and trailing edge configuration. A complete study of the aerodynamic behavior of the NACA 4421 airfoil under different methods of modification is shown in order to perform a detailed comparison between the modification methods.

1 U.S National Advisory Committee for Aeronautics dissolved in 1958 and transferred to the National Aeronautics and Space Administration (NASA).

METHODS

The CFD simulations were done using Ansys CFX 11®. CFX Mesh ® and were used to create the mesh. A two-dimensional solution was obtained by modeling the airfoil using two symmetry boundary conditions and a 2-D extruded mesh.

In the following section the parameters of the mesh are presented along with some validation cases. Next, a description of the modification methods is given. Finally, the two differently designed experiments are explained and the design criteria are mentioned.

COMPUTATIONAL MODEL

A two-dimensional grid was developed by creating a one element wide extruded mesh. The control volume has the far field at 30 chord lengths. The grid spacing over the airfoil surface consists of a relative curvature error of 1%, a minimum edge element length of 5 X 10^{-4} (2), a maximum edge element length of 1.2 X 10^{-3} (2) and an expansion factor of 1.2. The boundary layer region was modeled using 20 prismatic elements (structured mesh) over a thickness of 4 X 10^{-3} (2). The total surface points obtained are in the order of 2000 (Figure 1). The Delaunay method was used to produce the surface meshing. The total number of elements is about 90,000.

The turbulent model used was the two-equation k-ω shear stress transport (SST) model developed by Menter [17]. The model provides highly accurate predictions of separated flows from a smooth surface where adverse pressure gradients are found. Bardina [18] showed that the SST model has an overall improved performance compared to the other two-equation models, especially in terms of boundary layer separation prediction.

VALIDATION CASES

Computational results for the NACA 2212 and NACA 0015 airfoils are compared to the experimental data taken from the NACA Report No. 460 [19] with the purpose of CFD validation. Fig. 2 shows adequate agreement between the experimental and computational data, especially in the linear region, where CFD results predict lift and drag coefficients properly. Computational lift and drag coefficient curves tend to be over predicted, especially near the maximum lift angle of attack, but a certain amount of variability is expected in the stall region. The degree of stability of the lift curve near the critical angle of attack (lift-curve peak form) is known to be the function of the leading edge radius as discussed in the reference [18]. The surface flow separation is adequately modeled since the lift's curve sudden decrease and the

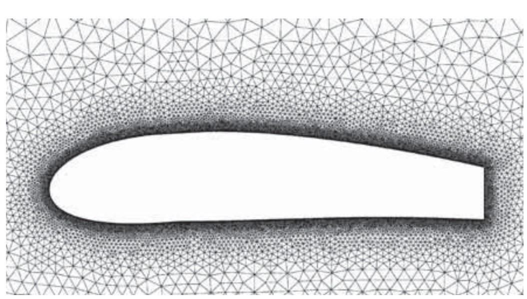

Figure 1. Mesh Example for the Modified NACA 4421 with a Trailing Edge Thickness of 0.12 (2) Using Adding Thickness Method

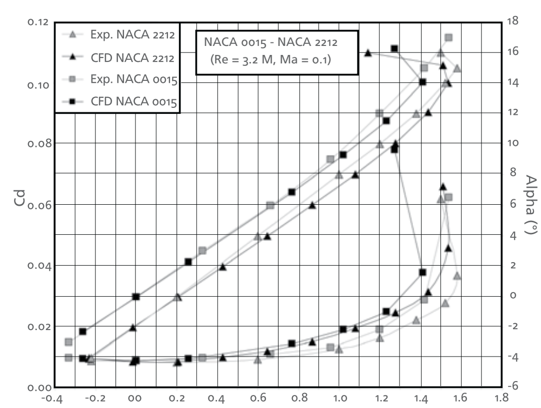

Figure 2. Validation Cases Results

2 All dimensions are based upon unitary chord length.

drag's coefficient sudden increase take place at angles of attack around the experimental value.

MODIFICATION METHODS

Two different airfoil modification methods were considered: the cutting off method and the added thickness method. The cutting off or "truncating" method consists of removing a segment from the rear portion of the baseline airfoil and then re-scaling the airfoil to its original chord length. The amount of airfoil cut off is interpolated in order to obtain the desired trailing edge thickness. As mentioned before, the problem with this method is that the shape of the new airfoil has a larger thickness and a lower camber. Another problem is that the chord line orientation is affected, hence creating a difference in the angle of attack definition (Figure 3). The camber reduction and the change in the angle of attack definition reduce the lift coefficient over the entire range of angles of attack.

The second method consists in symmetrically adding thickness along the baseline airfoil starting from a point ξ between the 30% and 50% marks of the chord (Figure 4). This point is studied to understand the noises that will be introduced if a series of experimental probes are manufactured with a removable trailing edge. The added thickness is carried out by defining a growing exponential function that has a zero value at ξ and that allows the acquiring of the desired trailing edge thickness. The main advantage of these methods of airfoil modification is that they preserve important geometric aspects of the airfoil such as airfoil thickness, camber line, chord line orientation and "nose geometry" [20].

TAGUCHI METHOD

A signal to noise ratio experiment as described by Taguchi [16] was designed to study the four-digit NACA airfoil family under different modification methods. This family was selected because its airfoils can be parameterized using three values: mean camber (first digit), camber position (second digit) and airfoil thickness (third and fourth digits). A total of sixteen modified airfoils were studied (L_{16} matrix), each under three different noise levels. The factors that describe each modified airfoil and their levels are: modification method (*cutting off (R), added thickness with* $\xi = 0.3$, $\xi = 0.4$ *and* $\xi = 0.5$), trailing edge thickness (*0, 5, 10, 15*), mean camber (*2, 4, 6, 7*), camber position (*2, 4, 6, 7*) and airfoil thickness (*12, 15, 21, 24*) (3) [19]. Table 1 lists the airfoils studied.

The noise levels are obtained by modifying the Reynolds number of the simulation group around the typical Reynolds number reported by NACA [19]. Reynolds

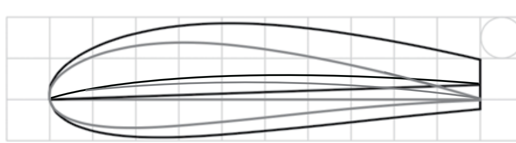

Figure 3. Cutting off Method

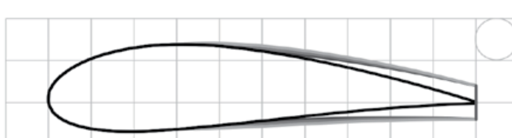

Figure 4. Added Thickness Methods

Naca 2212 R 00	Naca 4624 ξ(0.3) 00
Naca 4415 R 05	Naca 2721 ξ(0.3) 05
Naca 6621 R 10	Naca 7215 ξ(0.3) 10
Naca 7724 R 15	Naca 6412 ξ(0.3) 15
Naca 6715 ξ(0.4) 00	Naca 7421 ξ(0.5) 00
Naca 7612 ξ(0.4) 05	Naca 6224 ξ(0.5) 05
Naca 2424 ξ(0.4) 10	Naca 4712 ξ(0.5) 10
Naca 4221 ξ(0.4) 15	Naca 2615 ξ(0.5) 15

Table 1. Airfoils Studied

3 Trailing edge thickness, camber and airfoil thickness in percent of the chord length. Camber position in tenths of the chord length from the leading edge.

numbers of 2.6 million, 3.2 million and 3.8 million were simulated. Simulations for thirteen angles of attack were carried out for each airfoil.

The 2-D lift coefficient (C_l), drag coefficient (C_d), lift-drag ratio (L/D) and quarter chord moment coefficient (C_m) are calculated for each even angle of attack from -4° to 20°.

The output parameters derived are: angle of zero lift ($\alpha@C_{lo}$), maximum lift coefficient ($C_{l\ max}$), critical angle of attack ($\alpha@C_{l\ max}$), minimum drag coefficient ($C_{d\ min}$), maximum lift to drag ratio (L/D_{max}), angle of maximum lift to drag ratio ($\alpha@L/D_{max}$).

This experiment allows us to recognize the way the effects of main geometric parameters interact with the modification parameters by analyzing the mean value of an output variable through each factor level. Although this does not permit us to derive equations that describe the principles, it will show the overall behavior.

NACA 4421 STUDY

A detailed study of the NACA 4421 airfoil under different methods of modification was conducted. The airfoil was modified using the cutting off (R) and added thickness ($\xi = 0.3$, $\xi = 0.4$ and $\xi = 0.5$) methods while obtaining a trailing edge thickness of 4, 8, 12, 16 and 20 percent of the chord length, for a total of 20 different modified NACA 4421 airfoils studied. Pressure coefficient distribution is calculated for each airfoil for even angles of attack.

A complete detailed analysis of a single airfoil is required in order to quantify the effect of the modification and to fully understand its effects on aerodynamic performance. In order to accomplish this, the following output variables are studied: The lift curve slope ($m = dC_l/d\alpha$), angle of zero lift ($\alpha@C_{lo}$), maximum lift coefficient ($C_{l\ max}$), critical angle of attack ($\alpha@C_{l\ max}$), maximum lift to drag ratio (L/D_{max}), angle of maximum lift to drag ratio ($\alpha@L/D_{max}$), minimum drag coefficient ($C_{d\ min}$), and quarter chord moment coefficient at zero lift (C_{mo}).

RESULTS

In this section the results from both studies are presented. For the four-digit NACA airfoil family the results are shown in terms of the mean of the output variable through a specific factor level. The results given for the NACA 4421 study are shown as output variable vs. trailing edge thickness curves.

FOUR-DIGIT NACA AIRFOIL FAMILY RESULTS (FIGURES 5, 6)

The airfoil modification effect on stall region is shown in Fig.5. Added thickness methods produce a higher maximum lift coefficient than the cutting off method, especially for ξ of 0.4. Trailing edge thickness increases the maximum lift coefficient and the critical angle of attack, whereas airfoil thickness produces the opposite effect. The camber (first digit) increases the stall angle, while the camber position (second digit) decreases it.

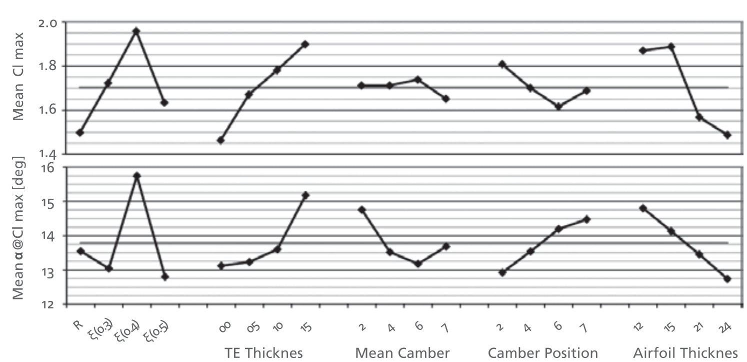

Figure 5. Airfoil Modification Effect on Stall

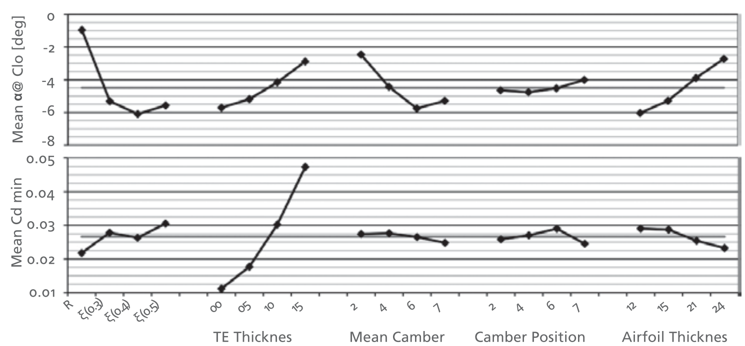

Figure. 6 Airfoil Modification Effect on α@Clo and Cd_{min}

Figure 6 shows the airfoil modification effect on zero lift angle and minimum drag coefficient. Trailing edge thickness produces a higher $\alpha@C_{lo}$ for the cutting of method, as well as a higher C_d for all the modification methods studied. Mean camber reduces the $\alpha@C_{lo}$, hence producing a higher C_l curve, while airfoil thickness increases the $\alpha@C_{lo}$. Modification effects on L/D [19] consist of an L/D_{max} reduction and a gliding angle ($\alpha@L/D_{max}$) increase as the trailing edge thickness increases.

NACA 4421 RESULTS (FIGURE 7-10)

The trailing edge thickness effect on the C_l curve for each method of modification is depicted in Figure 7. While the cutting off method increases the lift coefficient curve slope and produces a larger $\alpha@C_{lo}$, the added thickness methods increase the lift slope by a less significant amount, but produce no $\alpha@C_{lo}$ change. Figure 8 illustrates the effect on stall of the trailing edge thickness for each modification method. The trailing edge thickness increases and delays the Cl max for all the methods, but with a higher intensity for added thickness methods.

The trailing edge thickness effect on the lift to drag ratio appears to be independent from the airfoil modification method. The trailing edge thickness decreases the L/D_{max} and increases the gliding angle of attack. Additionally, the cutting off method produces lower zero lift moment coefficients, while added thickness methods produce higher ones [20]. C_d augmentation is larger for added thickness methods as depicted in Figure 11.

Pressure coefficient distribution for cutting off and added thickness ξ (0.4) methods are illustrated in Figures. 9-10. Trailing edge thickness avoids flow separation for both methods. This is depicted in Figures. 9–10, as for an angle of attack of -8° the NACA 4421 airfoil has a flow separation in the upper surface at 0.72 based unit chord position but the flow separation disappears for every modified airfoil. The cutting off method reduces the maximum suction C_p as the trailing edge thickness increases and produces C_p distributions such that the overall adverse pressure gradient on the upper surface is decreased. The added thickness method maintains the C_p distribution throughout most of the chord. This method reduces the overall adverse pressure gradient on the upper surface and it alters the distribution near the trailing edge [20]. For angles of attack with flow separation, added thickness methods increase the maximum suction C_p (Figure 10). In addition, the pressure distribution is altered at the start addition point (ξ) locations

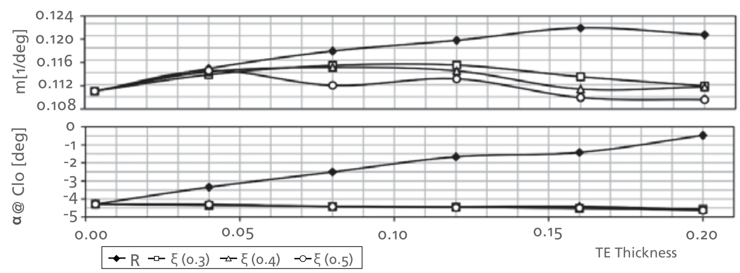

Figure 7. Trailing Edge Thickness Effect on Lift Curve Linear Region

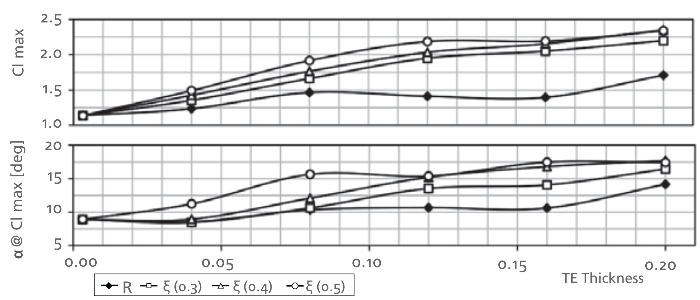

Figure 8. Trailing Edge Thickness Effect on Stall

on both surfaces, but with a higher intensity in the upper surface (Figure 10).

DISCUSSION

For all the airfoil modification methods studied the trailing edge thickness produces a larger maximum lift coefficient at a larger angle of attack, an overall increase in the drag coefficient and a decrease in the maximum lift to drag ratio. Increases in the gliding angle of attack, a delay of flow separation, as well as a reduction in the adverse pressure gradient in the upper surface are also effects of a thicker trailing edge.

The cutting off method produces modified airfoils with higher airfoil thickness, smaller mean cambers and a new chord line orientation. These geometric changes cause the following effects:

- Displacement in the lift curve (zero lift angle of attack increase) is mainly caused by the chord line orientation and by the maximum camber difference.
- Trailing edge thickness increases the lift coefficient curve slope to a maximum then decreases it again.
- Maximum lift coefficient and stall angle of attack increases are the result of an overlap effect between opposite effects: trailing edge thickness increases both, but airfoil thickness and lower camber decrease them both. This overlap effect continues to

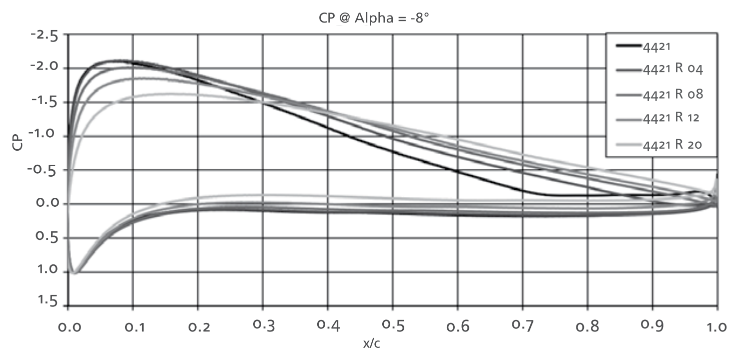

Figure 9. Cutting off Method Effect on Pressure Coefficient Distribution

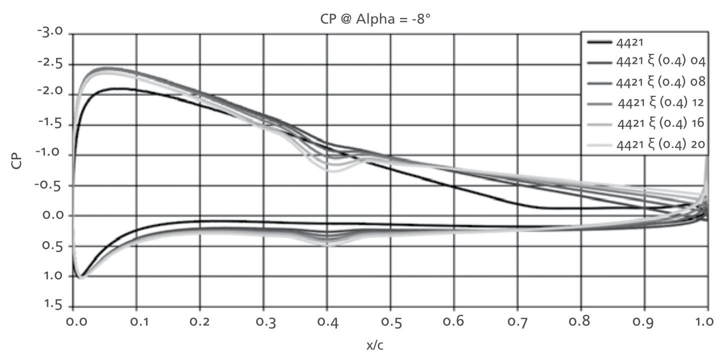

Figure 10. Added Thickness Method Effect on Pressure Coefficient Distribution

appear as the trailing edge thickness has an overall opposite effect to mean camber and airfoil thickness on the aerodynamic performance.

- Pressure coefficient distribution is altered by the geometric differences, reducing the maximum suction pressure coefficient.

The added thickness method produces airfoils that conserve the airfoil thickness, camber line distribution and chord line orientation; consequently the lift curve displacement is not present. This method allows separating the effect of the modification parameters on the aerodynamic performance. The following effects are recognized:

- Trailing edge thickness produces a small variation in the lift coefficient curve slope but produces no zero lift angle variation.
- Maximum suction pressure coefficient is not altered by these modification methods for angles of attack with no flow separation but it increases for flow separation angles. However, the pressure coefficient distribution varies near the trailing edge.
- ξ creates small variations in the pressure coefficient distributions, but it does not create major differences in the lift and drag coefficient curves [20].

Figures 11-12 show the lift, drag and moment coefficient curves, in addition to the lift to drag ratio curve for modified airfoils with a trailing edge thickness of 0.08 chord length.

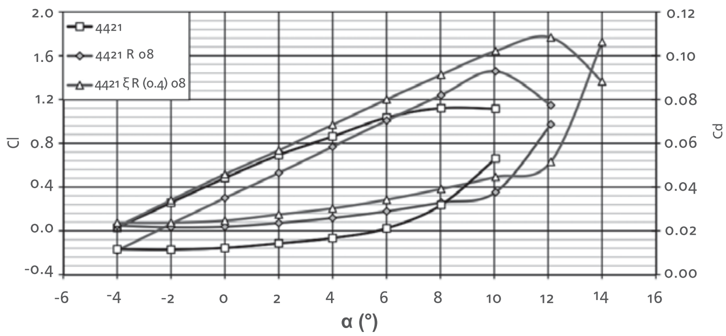

Figure 11. Effect of Trailing Edge Modifications on Lift and Drag (Re 2x10^6)

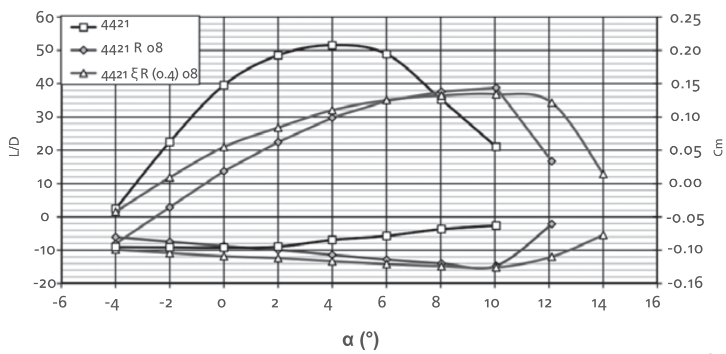

Figure 12. Effect of Trailing Edge Modifications on Lift to Drag ratio and Zero Lift Moment (Re 2x10^6)

The lift coefficient curve is larger for the added thickness method over the entire angle of attack range; in particular, it has a maximum lift coefficient which is 21% larger than the cutting off one. The drag coefficient increase is smaller for the cutting off method than for the added thickness method. The main cause for drag increase is the base drag caused by the pressure distribution in the trailing edge (wake pressure recovery), but the discrepancy in the drag increase between the methods is caused by the smaller surface drag produced by the lower mean camber of the cutting off method. The zero lift moment coefficient does not vary for the adding thickness method, but it increases for the cutting off method.

CONCLUSIONS

Two different blunt trailing edge airfoil modification methods have been previously investigated. The cutting off method was typically considered in the literature. Positive and negative effects on the aerodynamic performance of the cutting off method have been reported since this method leads to a change in camber, airfoil thickness and chord orientation. The added thickness method has been formerly pointed out as a method that allows the full differentiation between the effects of airfoil geometric parameters and modification parameters.

The added thickness method proved to have better lift enhancement than the cutting off method because it does not reduce the mean camber and does not increase the airfoil thickness.

A computational statistical study of the four-digit NACA airfoil family has been completed, along with a detailed computational study for the NACA 4421. The statistical analysis is a proper method of recognizing cause-effect relations, as well as detecting opposite effects in the aerodynamic performance of geometric and modification parameters.

The improvement in the lift coefficient of blunt trailing edge airfoils was studied, as they have a larger maximum lift coefficient and a larger stall angle of attack than unmodified airfoils. This holds true for all the modification methods studied. The top maximum lift coefficient achieved is 2.35 for the NACA 4421-ξ(0.4)-20, a 20% based chord length trailing edge thickness airfoil obtained using the added thickness method, compared to 1.15 lift coefficient of the unmodified NACA 4421. Additionally the stall angle increases to around 17.5° compared to 10° for the unmodified airfoil.

These improvements in the overall behavior near the stall point have implications on the wind turbine design. The use of blunt trailing edge airfoils in the root section of the blade may conduct to improve the wind turbine torque and power coefficients, as they will replace non-efficient thick airfoils and will operate at high angles of attack, producing high lift coefficients, hence increasing the root contribution to power. Additionally, it is believed that the use of thick trailing edge airfoils in wind turbine blade designs will produce wind turbines with stall control abilities, as they could have power coefficient vs. tip speed ratio curves without the undesired loss in power; a disadvantage of stall control [21]. Further research into this topic is required.

Drag increase and acoustic emissions could be considered as a drawback of blunt trailing edge modification. Tanner [22] studied methods for reducing base drag in flatback airfoils using different trailing edge forms including 2D and 3D devices. It was shown that a drag reduction of 50 to 60% can be achieved, for example a splitter plate on the trailing edge can reduce half of the base drag force.

As more information and data on this topic have been obtained by computational fluid dynamics, future efforts should focus on obtaining a complete range of experimental data that will confirm the results of the trailing edge modification methods. Future research should focus on the modification of commercial wind turbine airfoils, in particular on the airfoils with a total thickness larger than 30% of the chord length as they are used in the root region of the blade.

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Recibido 31 de agosto de 2009, aprobado 7 de marzo de 2011.