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Serrations effect on the aerodynamic performance of wind turbine airfoils

Elena Llorente * **and Daniele Ragni** †

* Nordex Energy Spain S.A.U., Avenida Ciudad de la Innovacion, 3, 31621 Sarriguren, Navarra, Spain

† Delft University of Technology, Kluyverweg 1, 2629 HS Delft, The Netherlands

E-mail: ellorente@nordex-online.com

Abstract. A numerical and experimental analysis of the trailing edge serrations effect on the aerodynamic performance of the NACA$64_3$418 airfoil is presented. 3D Reynolds-averaged Navier-Stokes simulations (RANS) of the flow over the airfoil with and without trailing edge serrations have been carried out with the Transitions SST turbulence model. From these calculations an empirical law for the prediction of the aerodynamic behaviour of the airfoil with serrations is derived. The law is validated through wind tunnel experiments. The NACA$64_3$418 airfoil has been tested with trailing edge serrations installed with different flap angles to analyze the effect of the parameter on the performance of the airfoil. Results show that the trailing edge serrations cause a significant increment in lift coefficient with low penalties in drag.

1. Introduction

Reducing the noise impact of wind turbines is a main topic in the wind industry. Serrated trailing-edges are very popular in industrial applications due to their simple manufacturing, installation and maintenance compared to other solutions like brushes or porous materials [1, 2, 3]. An increasing number of wind turbines manufacturers are offering, in their blade technology, the serration devices as a solution for obtaining high power production with low noise impact, including its effect in the blade design [4]. New business opportunities have been opened due to the possibility of using these devices for retrofitting existing machines that are already operational with "ad hoc" tuning of the operational regimes for noise regulations limits. During the last years a significant number of studies have focused on understanding of the noise reduction mechanism of the trailing edge serrations [5, 6, 7] but a clear gap in knowledge about their impact on the aerodynamic performance of the machine exists. This study focuses on the analysis of the effect of the trailing edge serrations on the aerodynamic performance of a wind turbine airfoil, the NACA $64_3$418. 3D RANS simulations have been performed using the Transition SST model [8] to quantify the changes in the aerodynamic performance of the airfoil due to trailing edge serrations. As a result of this analysis an empirical law for predicting the lift coefficient of the airfoil with serrations from the original data has been derived. This law includes the effect of serrations flap angle (the angle between the chord of the airfoil and the trailing edge extensions). This predicted law has been validated using wind tunnel experiments carried out at TU-Delft. The NACA $64_3$418 airfoil has been tested with and without trailing edge serrations installed with different flap angles. The influence of these devices and its assembly angle on the aerodynamic behaviour of the original airfoil has been analyzed.

2. Computational test-case

Three dimensional simulations of the airfoil NACA64$_3$418 with and without trailing edge serrations have been carried out using the Transition SST model from ANSYS [8]. C-types structured and non-structured meshes have been generated for the discretization of the 3D domains using ICEM CFD. The airfoil has been simulated with a chord of 1 m and its shape has been modified from sharp trailing edge to a thickness of 0.2% of the chord. Serrated trailing-edges have been modeled by periodic inserts of length of 2h = 0.187 mm and amplitude of λ = 0.140 mm, as shown in Figure 1. A ratio between streamwise and spanwise length of the serrations of $\frac{\lambda}{2h}$ = 0.75 has been selected for best performance in noise reduction in the mid-frequency range with small noise penalties in the high one [9].

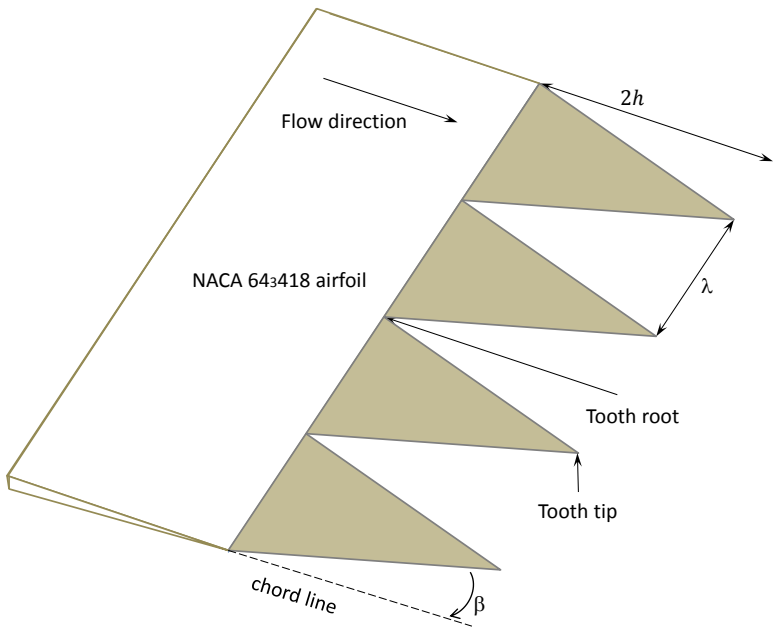

Figure 1: Scheme of the serrations with length of 2h and amplitude of λ.

3. Numerical results

In this section the aerodynamic coefficients for the original NACA64$_3$418 airfoil with and without trailing edge serrations are presented. It must be noted that for all the simulated cases, the aerodynamic coefficients are obtained using the chord of the original airfoil without including the length of the trailing edge serrations. In Figure 2 the lift and drag coefficients for different angles of attack for the airfoil with and without trailing edge serrations are compared. These results show that for all the studied angles of attack the serrated extensions do not significantly change the lift coefficient of the airfoil but cause an increment in the drag coefficient.

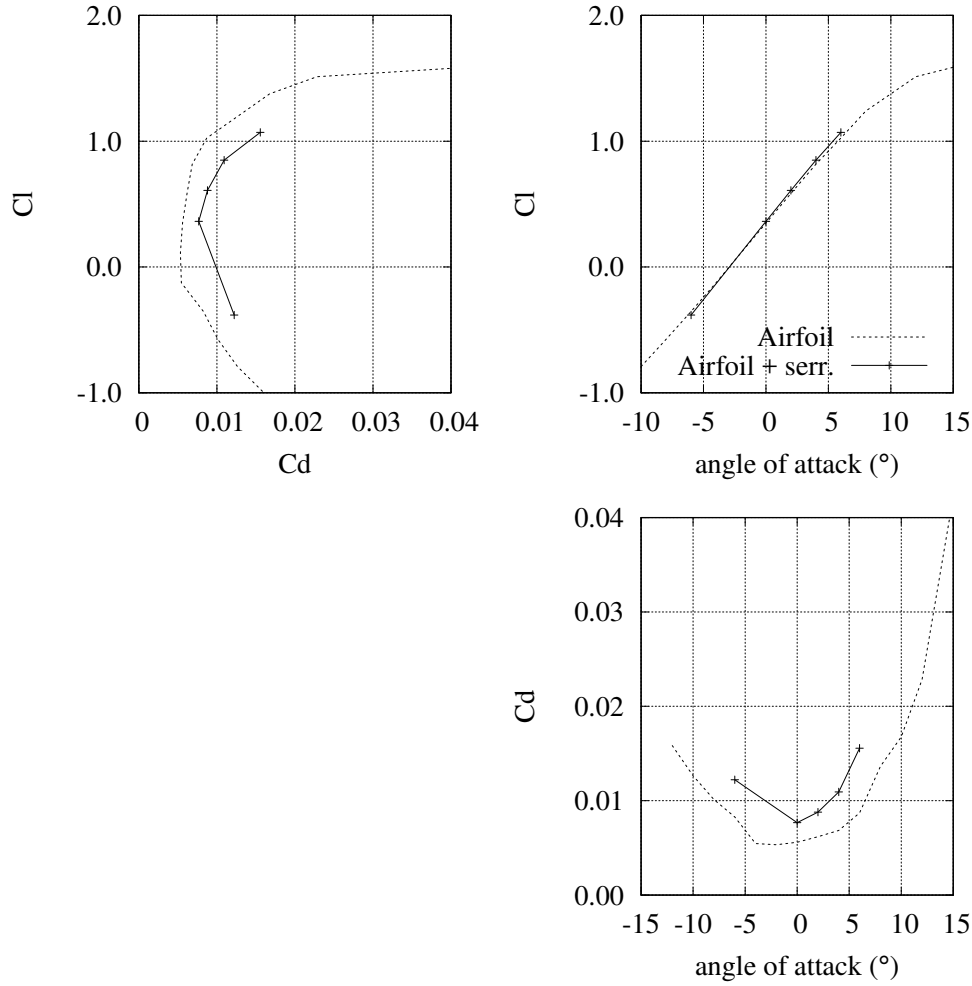

Figure 2: Polar data of the NACA64$_3$418 airfoil with and without trailing edge serrations.

The simulated results show that the trailing edge serrations affect the aerodynamic behaviour of the airfoil in which they are installed. To predict this impact trying to avoid the costly CFD simulations the linear thin airfoil theory [10] has been used to derived a law that can calculate the lift coefficient of the serrated airfoil using the data of the original profile. With this theory, first the lift coefficient of the airfoil without any extensions is derived in Equation 1:

$$Cl_a = 2\pi\alpha + Cl_0 \tag{1}$$

Applying the same methodology the lift coefficient of the airfoil with trailing edge serrations can be obtained using the Equation 2.

$$Cl_{as} = 2\pi\alpha(1 + l_s/c) + 2\pi\beta l_s/c + Cl_0 \tag{2}$$

where the lift coefficient is obtained as a function of the angle of attack (α), the flap angle (β), the length of the serrations (l_s), the chord of the original airfoil (c) and the lift at zero angle of attack of the original airfoil (Cl_0).

With this proposed equation an accurate estimation of the lift coefficient of an airfoil with trailing edge serrations could be obtained from the data of the original airfoil reducing the necessity of CFD calculations or wind tunnel experiments for calculating the influence of these extensions on the aerodynamic behaviour of an airfoil.

4. Validation

The previous equation has been validated through wind tunnel experiments. In this section the results obtained from the experimental measurements of the NACA$64_3$418 airfoil with and without trailing edge serrations installed with different flap angles has been displayed and compared with the predicted by Equation 2.

4.1. Experimental set-up

In order to validate the previous law, wind tunnel experiments have been performed. These tests have been accomplished in the low speed low turbulence wind tunnel of TU-Delft. It is an atmospheric tunnel of the closed-throat single-return type, with a contraction ratio of 17.8. The test section is 1.80 m wide, 1.25 m high and 2.60 m long. It has a 2.9 m diameter six-bladed fan driven by a 525 kW DC motor, giving a maximum test section velocity of about 120 m/s. The free-stream turbulence level in the test section varies from 0.02% at 25 m/s to 0.07% at 75 m/s. Electrically actuated turntables flushed with the test-section top and bottom wall provide positioning and attachment of several two-dimensional models, which can be operated at several angles of attack. The centre of rotation for all the models is set at half chord distance. The free-stream velocity is monitored by evaluation of the free-stream dynamic pressure q_0 through a calibration curve from the tunnel contraction control pressure Δp_b, measured as the difference between the settling chamber total-pressure and the wall (static) pressure at a station about half-way in the contraction. The static pressure at the contraction is evaluated as the average of 4 static-pressure taps distributed at the circumference of the tunnel. In this facility, lift and drag are typically measured with a six-degrees of freedom multi-component balance connected to the model. In this particular study, the aerodynamic forces and pressure distribution could be easily obtained from pressure ports distributed on the pressure and suction side of the models. The drag of the airfoil is instead obtained from integration of the measurements from a wake rake of Pitot tubes installed at a distance of half meter downstream the airfoil. The free-stream total-pressure is calculated as an average of all the wake-rake total-pressures outside the wake of the airfoil. Finally the free-stream static-pressure is calculated as the difference between the total pressure from the wake rake and the dynamic pressure from the tunnel controller. The maximum Reynolds number achieved for the tests was $Re_c = 1 \cdot 10^6$. The NACA$64_3$418 model was built into an aluminum wing with 250 mm of chord and a span of 1225 mm. In this model 50 pressure tabs were installed for instrumentation, 25 in each side for measuring the forces over the model, the pressure tabs features a 13-degrees offset in span-wise direction to avoid mutual pressure orifices interference. The length of the serrations was 2h = 75 mm with $\frac{\lambda}{2h} = 0.75$. Three different flap angles using the same shape have been tested, 0°, 5° and 10°. The trailing edge serrations have been manufactured in aluminum and have been installed at the pressure side of the model using screws. An aluminum tape for ensuring a smooth transition between the model and the attachment of the trailing edge extensions has been used. Due to the trailing edge curvature of the pressure side of the metallic model during the installation of the devices a correction on the flap angle has been done. In Figure 3 a picture of the model with trailing edge serrations placed in the wind tunnel test section is presented.

Figure 3: NACA64$_3$418 model tested in the wind tunnel.

4.2. Experimental results

In Figure 4 the aerodynamic coefficients for the NACA64$_3$418 airfoil with and without trailing edge serrations have been displayed. It is important to remark that to the measured data the standard wind tunnel wall corrections for lift-interference and model solid and wake blockage as given by Allen and Vincenti [11] were applied. Corrections have also been made for the effect of solid blockage of the wake rake on the test section velocity and the effect of the wake rake self-blockage on the values of the static pressures (and consequently the dynamic pressure) measured by the wake rake [12]. It is clear that the impact of the trailing edge serrations cause a significant increment of the lift coefficient mostly at angles of attack from 5° to 15°. Analyzing the drag curves, smaller differences between the serrated and the original airfoil were measured. Looking into the flap angle effect it is shown that the increase of this angle has a positive effect on lift and a slight negative effect on drag causing a gain in the efficiency of the airfoil. This effect changes for large flap angles generating efficiency looses when the flap angle is highly increased, for this airfoil the most effective flap angle is 5°.

It is remarkable the hysteresis loop at positive and negative stall angles of attack. The hysteresis means the difference in lift and drag coefficients at a given angle of attack when this angle is approached from higher or lower values. It is a sign of a large, laminar separation which in turn yields high bubble drag [13]. As it is shown in Figure 4 this hysteresis cycle is not affected by the presence of serrated extensions due to the sensitivity of the bubble to the peak pressure gradient in proximity of the nose.

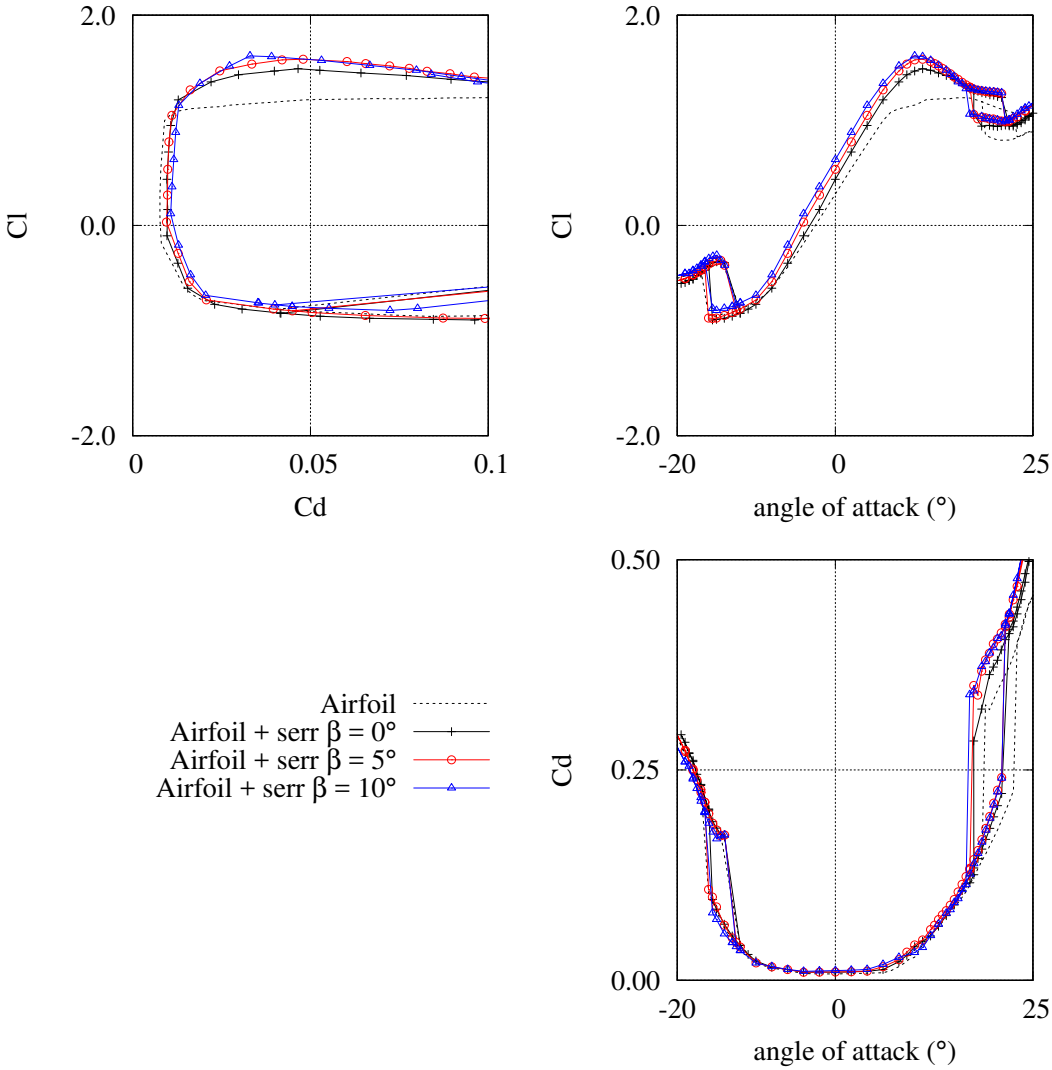

Figure 4: Aerodynamic coefficients for the NACA64$_3$418 with and without trailing edge serrations varying the flap angle.

In Figure 5 a comparison between the experimental results of the wind tunnel tests and the predicted by Equation 2 for different flap angles are displayed. In this plot it can be observed that for the different flap angles tested in the wind tunnel the proposed law predicts correctly the lift coefficient of the airfoil with trailing edge serrations from the data of the original profile. With this predicted law the influence of the trailing edge serrations on the whole blade can be obtained and the impact of these extensions on the power production or loads of the wind turbine can be calculated.

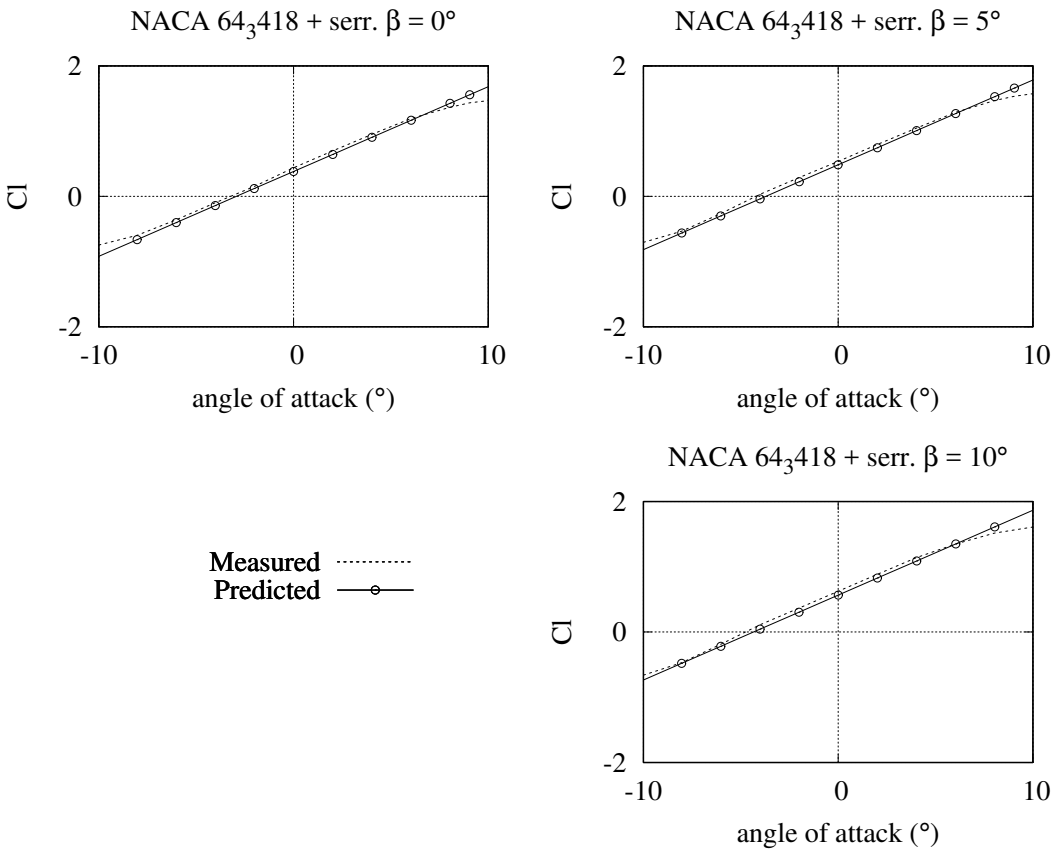

Figure 5: Comparison between the predicted and measured lift coefficient for the NACA$64_3$418 airfoil with trailing edge serrations varying the flap angle.

5. Conclusions

A numerical and experimental study of the aerodynamic impact of the trailing edge serrations on the NACA$64_3$418 airfoil has been presented. CFD simulations of the airfoil with a without trailing edge serrations show that the trailing edges serrations have an impact on the aerodynamic coefficients of the airfoil. Using these results a prediction law has been derived. With this equation the lift coefficient of the airfoil with serrations can be obtained from the data of the original profile. This equation has been validated using wind tunnel tests performed in the TU-Delft facilities and it shows a good agreement with the experimental data. The tests show a significant increment in lift coefficient due to the presence of the trailing edge extensions, the drag coefficient is also increase although at a reduced rate. In these experiments the flap angle effect is also analyzed, its increment caused a gain in lift and the penalty in drag is really slight. For this case the most effective flap angle is the intermediate one ($\beta = 5°$), increasing too much this angle cause bigger drag penalties and slights lift gains so the efficiency of the airfoil is reduced.

It can be concluded that the efficiency of the airfoil is increased by the presence of trailing edge extensions and its effect can be predicted with a simple equation that permits obtaining the lift coefficient of different airfoils with trailing edge extensions from the data of the original ones. With this information the power curve and the loads of a wind turbine with trailing edge extensions can be calculated without using costly CFD simulations or expensive wind tunnel tests, and its effect can be included in the design loop of the low noise new blades.

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