A PIV LOAD AND FLOW STRUCTURE STUDY OF A SERRATED DYNAMIC AIRFOIL

Kobra Gharali¹, Nicholas Tam¹, David A. Johnson¹*

¹: Wind Energy Group, Department of Mechanical and Mechatronics Engineering, University of Waterloo, Waterloo, Canada
* correspondent author: david.johnson@uwaterloo.ca

Abstract Noise reduction utilizing serrated airfoils has been considered recently with a wide range of applications including wind turbine blades. In this study, with the aid of the Particle Image Velocimetry (PIV), the flow structure of a serrated dynamic airfoil and calculated lift values using the control volume approach reveal more details about the effects of the serration. An oscillating SD7037 airfoil modified with either a serration or a flat-plate is investigated at Re 40,000 with the reduced frequency of 0.08 while the airfoil experiences deep dynamic stall phenomena. Existence of deep dynamic stall vortices provides the opportunity to investigate the effects of the serration on vortices. A comparison of the lift cycles shows that at low angles of attack, there is no significant load difference between the serrated case and the original case, but at high angles of attack after the first leading edge vortex formation; significant load increments due to the serration were observed. The comparison of the leading edge vortex circulation shows that serration does not enrich the leading edge vortex circulation; thus, another reason such as trailing edge vortices should affect the lift values. For the flat-plate case, the lift increase agrees with its leading edge vortex circulation enrichment. At low angles of attack, the frequency of vortex shedding decreases when the airfoil is modified by the serration or the flat plate. Vortices also disappear faster in the wake for the serrated case.

1. Introduction

The growth of wind energy for power generation has been expanding globally. Despite its rapid growth, acceptance of wind turbines is far from universal. One common criticism of wind turbines is noise emissions. Accordingly, many jurisdictions have set up guidelines limiting noise levels from wind turbines. The control and reduction of acoustic emissions is therefore a subject of much interest to the designer and the operator of wind turbines alike. As noted by Oerlemans et al., it is recognized that the major noise source of a well-designed wind turbine originates from aerodynamic sources [10]. Various methods have been explored in response to the aerodynamic noise issues; among them, saw tooth serrations have been found effective in reducing overall noise emissions. They can be applied to existing wind turbines with little to no modification to existing blades or components; making it ideal to correct noise issues after installation. In particular, the simplicity of its implementation makes it also useful for small scale wind turbine applications.

The effects of saw tooth serrations were first predicted analytically by Howe for a flat-plate in low Mach number turbulent flow [8]. The introduction of serrations reduced the effective spanwise length of the trailing edge. This impacted the efficiency of noise generation caused by the convection of turbulence boundary layer over the trailing edge [8]. From experiments, the noise reduction behaviour was found to be different than Howe’s predictions. Dassen et al. found that noise reduction up to 8 dB was achieved with airfoils in controlled wind tunnel conditions [1]. Detrimental effects could occur when serrations were not aligned with the flow [1]. However, even optimally configured, reduction was below that predicted by Howe [1]. Experiments at an outdoor turbine by Oerlemans et al. had similar findings, with an average of 3.2dB reduction observed from a turbine blade modified with serrations [10]. Noise reduction behavior with respect to the acoustic spectrum was also found to be different in several studies [3, 6, and 9]. Serrations were only found to reduce noise in lower frequencies while increasing noise when the boundary layer Strouhal number is approximately greater than 1.
It was therefore of interest to examine the fluid flow phenomenon of the trailing edge serrations to determine the physical mechanism related to the cause of the noise reduction. Gruber attributes the mechanism related to serrations’ effects on the phase speed of turbulence convection near the trailing edge [6]. According to that study the interference between backscattering pressure and convected turbulence pressure is likely the cause [6]. The increase in high frequency noise experienced by the serrations is suggested to be related to the cross flow from the pressure side of the airfoil through the valley of the serrations [6]. Finez et al. observed the flow field of serrated airfoils in a cascade configuration using time resolved PIV. It was found that serrations have altered the flow field at the trailing edge. The attached turbulent boundary layer had been “blown off” due to the cross flow; suggesting this phenomenon may reduce the efficiency of noise generation [3]. There is also enhanced mixing, more rapid turbulence decay, resulting in a broader, less deep and less symmetrical wake [3]. The vortex sheet also vanishes faster than the straight edge case [3]. In terms of aerodynamic effects, both Gruber and Finez et al have found drag to increase by greater than 10% as a result of serrations [3 and 6]. In a study at low to moderate Reynolds number conditions, Moreau et al. conducted hot wire measurements in the tip and root of serrations. Velocity spectra showed vortex shedding is suppressed with serrations and hence associated noise is attenuated [9].

The studies of serrations in static conditions from the references above provided insights into its noise reduction mechanism. As wind turbine blade elements are subjected to highly dynamic oscillations while in operation, studying the behavior of serrations under oscillating angles of attack can provide a further understanding of how serrations perform under field conditions. This study focuses on the effects of the trailing edge serrations at low Reynolds number based on the flow structure and calculated lift values. In depth simultaneous studies of the fluid flow structure and aerodynamic loads are now possible with the Particle Image Velocimetry (PIV) technique due to progress in image processing and post processing. Load calculation based on the control-volume approach of PIV velocity fields has been extensively validated for static objects. The dependency of the unsteady forces of dynamic airfoils on many parameters makes applying this technique for dynamic airfoils more complicated. Some recent studies have been done for the dynamic case [2, 4, 12, and 13]. For the dynamic case of this study, the airfoil will also experience deep dynamic stall phenomena. Energetic dynamic stall vortices significantly challenge the load calculations from the PIV control volume approach, but give an opportunity to study the effects of the serrations on vortices.

2. Experimental Setup

The experiments were conducted at University of Waterloo with the Wind Energy Group’s low speed closed circuit wind tunnel. The wind tunnel has a test section of 152.4x152.4mm cross-section, generating wind speeds up to 30 m/s with turbulence intensity is less than 1%.

For the PIV setup, a Dantec Flowserve EO camera with resolution of 2048x2048 pixels was used. A Nikon 60mm focal length macro lens set at f 2.8 provides a field of view of approximately 1.73 times the chord length in the close view and 2.76 times chord length the wide view. The mid-plane of the test specimen is illuminated by a Nd:YAG pulsed laser at 532nm wavelength. Optics split the light to illuminate the top and the bottom of the airfoil. 500 image pairs were taken for each angular position. A small number of out of sync images were rejected from the analysis. The velocity fields of the remaining image pairs were analyzed using the Adaptive PIV method from Dantec Dynamic Studio software.

Oscillation of the airfoil is provided by a PID controlled servo motor. Angle accuracy of the setup is ±0.2°. At each user defined angle, the controller triggers the PIV system. The airfoil was oscillated according to

\[ \alpha = \alpha_{\text{mean}} + \alpha_{\text{amp}} \sin(2\pi ft) \]  

(1)

where \( \alpha_{\text{mean}} = 11^\circ \), \( \alpha_{\text{amp}} = 11^\circ \) with the reduced frequency \( k = \frac{\pi fc}{u} \) of 0.08.

For all experiments reported here, a SD7037 airfoil profile with chord length of 25mm was tested at a Reynolds number of 40,000. The SD7037 airfoil is recommended for low Reynolds number horizontal axis wind turbines.
Due to the small dimensions and thin trailing edge of this airfoil, serrations were cut from 5 mil polyester shim stock using a laser cutter. They were attached to the pressure side trailing edge using cyanoacrylate adhesives. Results are presented for a serrated airfoil ($\lambda/h = 0.67$), in comparison with the original airfoil and a flat-plate extension of the same wetted surface area. Details can be seen in Figure 1 and 2. Serration provides an additional 13.3\% extension of the chord (root to tip of serration). The dimensions of the airfoil including serrations allow tunnel blockage ratio to be less than 7\%.

![Diagram of Serrations](image1.png)

**Figure 1- Diagram of Serrations used in the study**

Variables - \( \lambda \): wavelength of serrations, \( h \): half of serrations amplitude

![SD-7037 airfoil with the attached serration](image2.png)

**Figure 2- SD-7037 airfoil with the attached serration**

3. PIV integral forces and pressure field determination

The control volume around the object with unit depth fixed in space is shown in Figure 3. According to linear momentum, the flow variables inside a control volume can be integrated for load calculation:

\[
\vec{F} = - \iiint_V \frac{d}{dt} (\rho \vec{U}) \, dV - \iiint_S \left[ \rho \vec{U} \cdot (\vec{n} \cdot \dot{\vec{n}}) \right] \, dS - \iiint_S \rho \vec{n} \, dS + \iiint_S (\tau \cdot \vec{n}) \, dS
\]

(2)

where \( \vec{n} \) is the unit outward vector and \( \vec{F} = \left[ \begin{array}{c} \vec{F}_d \\ \vec{F}_l \end{array} \right] \) for drag and lift values. Phase averaging of the oscillating case for this range of low reduced frequency results in elimination of the unsteady term. Then for incompressible flow, Equation (1) becomes

\[
\vec{F} = - \iiint_S \rho \vec{U} \cdot (\vec{n} \cdot \dot{\vec{n}}) \, dS - \iiint_S \rho \vec{n} \, dS + \iiint_S (\tau \cdot \vec{n}) \, dS
\]

(3)
where the overbar shows averaged values. By considering a 2D domain, a line or contour integration can replace the control surface integration. For the unknown pressure, integrating the Navier-Stokes equations provides the mean pressure. The tensor form of the pressure-gradient components is

\[
- \frac{\partial \sigma}{\partial x_i} = \rho U_j \frac{\partial \sigma_{ij}}{\partial x_j} + \rho \frac{\partial U_i}{\partial x_j} \frac{\partial U_j}{\partial x_j} - \mu \frac{\partial^2 \sigma_{ij}}{\partial x_i \partial x_j}
\]

(4)

![Figure 3- Sketch of the 2D control volume and control surface definitions for determining integral aerodynamic forces; right: control volume boundaries for a pitching airfoil during post stall superimposed with the vorticity field [4].](image)

4. Results and discussion

In this section, the values were made dimensionless with \(c + h\) for the flat-plate and serrated cases and with \(c\) for the original case.

4.1. Lift cycles

Figure 4 shows the PIV lift coefficient cycles for original, serrated and flat-plate cases when \(k = 0.08\). For all cases, two lift peaks in pitch up motion are observed. Thus, the number of the vortices during upstroke is not affected. The first lift peak during downstroke is also noticeable for all cases. The lift peak magnitude is decreased from the first upstroke peak to the second upstroke peak and also to the first downstroke peak. Based on the vortical structure, each lift peak indicates a developing leading edge vortex which meets the trailing edge of the airfoil; then, the PIV lift calculation method can capture the lift peaks; even those associated with weak vortices. The dynamic stall angle (the first upstroke lift peak) is reported 18.5° for the original case, but it is postponed to 19° and 19.5° for flat-plate and serrated cases, respectively. The second lift peak is at 22° for all three cases.

For the serrated case, at low angles of attack, the lift values are almost the same as the original airfoil. For the static case, at low angles of attack, Gruber [6] showed no significant lift differences between the original case and the serrated case; the current results agree with the static case, for low angles of attack before leading edge vortex formation. For the flat-plate case, at low angles, the lift values are higher than two other cases. It is assumed that the flat plate extends the length of the airfoil therefore the lift values are increased. When the Leading edge vortex forms close to \(\alpha = 15°\) \(\uparrow\) (upstroke or pitch up motion) a jump in the lift values for the serrated case is observed compared to the original case; the lift value at the dynamic stall angle is almost one unit higher than that of the original case. After the dynamic stall angle, the lift drops. Higher lift peak values result in lower lift drop as it is visible at \(\alpha = 21°\) \(\uparrow\). For the second lift peak (\(\alpha = 22°\)), the lift values again increased compared to the original one. For investigating the reasons of the lift curve behavior, a vortex study can be helpful.
4.2. Vorticity field

Figure 5 shows the vortical structures close to the dynamic stall angle. When the first developing leading edge vortex (blue vortex) during upstroke meets the trailing edge of the airfoil this results in the first maximum lift peak at the dynamic stall angle. For the original airfoil, at $\alpha = 18.5^\circ \uparrow$, the leading edge vortex meets the trailing edge and after that the trailing edge vortex (red one) starts rolling up which agrees with the lift reduction in Figure 4. For the serrated airfoil, at $\alpha = 18.5^\circ \uparrow$, the leading edge vortex meets the trailing edge of the airfoil, but since the serration has extended the length of the airfoil chord, the leading edge vortex keeps developing while its circulation increases. When the leading edge vortex meets the end of the serration, dynamic stall occurs at $\alpha = 19.5^\circ \uparrow$ and the trailing edge vortex starts rolling up which is visible at $\alpha = 20^\circ \uparrow$. Therefore, the dynamic stall for the serrated case is postponed about 1$^\circ$; thus, the circulation of the LEV is enhanced resulting in a higher lift peak value.

Figure 6 shows the vortical structures of the wake (one chord length) at $\alpha = 0^\circ$ when the flow is attached. For the serrated case, the shedding frequency is decreased compared to the original one. The vortices vanish faster which is consistent with Finez et al.’s results [3]. For the flat plate case, the frequency of vortex shedding decreases more, but the vortices stay longer in the wake.
Figure 5 Vortical structures; ↑: upstroke or pitch up motion, ↓: downstroke or pitch down motion.

Figure 6 A snapshot of trailing edge vortices for original, serrated and flat-plate cases at $\alpha = 0^\circ$.

4.3. Leading edge vortex circulation

Based on Stoke’s theorem, for a vortex located inside a rectangular area $A$, the circulation, $\Gamma$, can be calculated by integrating the vortex vorticity, $\omega_z$, as

$$\Gamma = \iint_A \omega_z \, dA;$$  \hfill (4)

For more details, please see [5, 11].

Comparison between Figures 4 and 7 reveals the contribution of the leading edge vortex to the lift trend. As expected, for the flat-plate case, the leading edge vortex circulation is higher than the original case for almost all angles. Therefore, the flat plate increases the overall circulation of the leading edge vortex which results
in overall higher lift values compared to the original case. For the serrated airfoil, the strength of vortex circulation is almost the same as the original case except close to the dynamic stall angle as discussed in Figure 6. Therefore, the serration, does not affect the leading edge vortex circulation except close to the dynamic stall angle. Thus, the lift increment at angles higher than static stall angle should be due to other reasons such as the trailing edge vortex. It should be noted that the trailing edge vortex has negative effects on lift augmentation.

5. Conclusions

At low angles of attack, there was reasonable agreement between the dynamic serrated case of the current study and the static serrated case from literature; for both static and dynamic cases at low angles of attack, no significant lift increase and also faster disappearing shedding vortices compared to the original cases were found. For the dynamic serrated airfoil the frequency of the shedding vortices decreased compared to the original case.

PIV lift calculation based on the control volume approach could capture all the events of the flow structure including lift peaks from the small leading edge vortices. For higher angles of attack after the first leading edge vortex formation, the lift values of the serrated case are higher than those of the original case while the circulation of the leading edge vortices are almost the same for both cases except close to the dynamic stall angle; thus, another reason such as the effects of the trailing edge vortex could cause the lift differences. The vorticity field showed that when the leading edge vortex meets the airfoil’s trailing edge for the original case dynamic stall was observed, but for the serrated case, the vortex kept developing until the end of the serration and then dynamic stall occurred. This delay in dynamic stall which is about 1° results in higher lift values close to the dynamic stall angle.

For the flat-plate case, the flat plate extended the length of the airfoil’s chord and did not show the same...
trends as the serrated case. In terms of the load study, the flat-plate case increased the lift values for all angles of attack and also the circulation of the leading edge vortex was higher than the original case. Thus, unlike the serrated airfoil, the flat-plate case showed a trend similar to a bigger airfoil.

6. References


