Effect of Wavy Trailing Edge on 100meter Flatback Wind Turbine Blade

SJ Yang¹ and J D Baeder²

¹ Graduate Research Assistant, Department of Aerospace Engineering, University of Maryland, College Park, MD 20742, United States
² Professor, Department of Aerospace Engineering, University of Maryland, College Park, MD 20742, United States

sjyang@umd.edu

Abstract The flatback trailing edge design for modern 100meter wind turbine blade has been developed and proposed to make wind turbine blade to be slender and lighter. On the other hand, it will increase aerodynamic drag; consequently the increased drag diminishes turbine power generation. Thus, an aerodynamic drag reducing technique should be accompanied with the flatback trailing edge in order to prevent loss of turbine power generation. In this work, a drag mitigation design, span-wise wavy trailing edge blade, has been applied to a modern 100meter blade. The span-wise trailing edge acts as a vortex generator, and breaks up the strong span-wise coherent trailing edge vortex structure at the flatback airfoil trailing edge which is a major source of large drag. Three-dimensional unsteady Computational Fluid Dynamics (CFD) simulations have been performed for real scale wind turbine blade geometries. Delayed Detached Eddy Simulation (DDES) with the modified laminar-turbulent transition model has been applied to obtain accurate flow field predictions. Graphical Processor Unit (GPU)-accelerated computation has been conducted to reduce computational costs of the real scale wind turbine blade simulations. To verify the structural reliability of the wavy modification of the blade a simple Eigen buckling analysis has been performed in the current study.

1. Introduction
Reducing weights while maintaining both power generation and structural reliability is perhaps the most challenging task for the modern over 100meter wind turbine blade design. Recent lighter blade designs will be equipped with ‘flatback’ trailing edge on a portion of the blade so that the rotor blade can have a shorter chord length. Consequently, the blade can be much lighter and slender. Furthermore its blunt trailing edge suppresses early flow separation onset compared to blades with sharp trailing edges. It is because the thickening of the trailing edge results in less airfoil surface curvature on the back half of the upper surface, and finally reduces the airfoil surface adverse pressure gradient. As a results the turbine doesn’t stall as easily.

Nonetheless of the benefits, the flatback trailing edge produces large aerodynamic base drag because of its highly blunt base shape. According to the classic findings of aerodynamics, the periodical Karman vortex structure downstream of the blunt base is a main source of the drag increase. Based on previous wind tunnel tests of the thick-flatback airfoils, such as FB3500–1700, and DU97-W300, the aerodynamic drag was seen to be 5~10 times larger than the thick-sharp
trailing edge airfoils within the angle of attack range of $4^\circ$ to $20^\circ$ [1][2]. The drag rise reduces the lift to drag ratio, resulting in a loss of turbine power.

Several methods of trailing edge modification have been proposed to try to break up the trailing edge vortex shedding of the flatback airfoils. Most of the modifications add the vortex breakup devices at the trailing edge: split plate, serrated plate, cavity, so on [3]. However, modifying the trailing edge shape itself may result in as much or more drastic changes to the trailing edge vortex structure. Varying the trailing edge thickness in the span direction will generate more cross flow in the span direction, resulting in more vigorous vortex breakup as compared with a split-plate or serrated-plates. In the current study, effects of the wavy trailing edge will be investigated via CFD as applied to the 100meter blade. An approximately 8meter length segment of the real scale 100meter blade rotation has been simulated for a common wind turbine operating condition.

2. Span-wise wavy trailing edge Design for Flatback Wind Turbine Blade
2.1 Basic Concepts

The main idea of the wavy trailing edge design is to modify the local trailing edge thickness in the blade span direction, so as to a produce span-wise wavy shaped trailing edge (Fig. 1). The wavy distributions at the trailing edge have been generated by a modified cosine formula as presented in Equation (1) and (2). In the formula, ‘x’ and ‘l’ represent the spanwise location and length of the waves while $y_{\text{max}}$, $y_{\text{min}}$ represent maximum and minimum heights from the chord line respectively, and ‘$\omega$’ is the wavy frequency. The ‘FB3500-1750’, and ‘FB3500-0462’ have been used as the baseline airfoils. Three different airfoils were created depending on the wave depth. The span-wise wavy trailing edge airfoils have been named with their wave parameters. For example, if the airfoil trailing edge wave has wave depth of 1/4 of the flatback trailing edge thickness and its wave length is 4 wave cycles per 1 chord length of span, then the airfoil will be named as ‘1/4 flatback – 4cyc/C’. Here, the ‘cyc’ means wave cycle, and the ‘C’ is the airfoil chord. In the previous works [4], after testing various design patterns, two wavy trailing edge designs, ‘3/4 flatback-4cyc/C’ and ‘1/2 flatback-4cyc/C’ shown in Figure 1 had been selected as the best primitive design candidates, regarding to the aerodynamic and aeroacoustic performance. In the previous CFD simulations, the selected designs showed lower drag for wind tunnel test conditions with $\text{Re} \sim 666k, M = 0.3$, as compared to the baseline flatback [4].

Figure 1. Basic concept of the wavy trailing edge modification and primitive designs
\[ \Delta y = y_{\text{max}} - y_{\text{min}} \]  \hspace{1cm} \text{Eq (1)}

\[ \text{local thickness} = \frac{\Delta y}{2} \left[ \cos \left( \frac{2\pi}{l} x + \frac{x}{l} \right) + 1 \right] + y_{\text{min}} \]  \hspace{1cm} \text{Eq (2)}

2.2 Previous Design Improvement: Structural Concerns

The primitive concept designs, ‘3/4 flatback-4cyc/C’ and ‘1/2 flatback-4cyc/C’, work well for drag reduction. However, in the real world of very large wind turbines, their relatively long and intense wave paves on the blade surface may increase structural concerns. Regarding to the potential structural issues, the wavy trailing edge design has been improved during the previous research steps as shown in Figure 2. The pattern No. 1 has wave paves that begin only very near the trailing edge (from 0.9 x/c to 1.0 x/c). The pattern No. 2 has the wave paves begin at maximum thickness (from 0.45 x/c to 1.0 x/c), but only on the bottom surface. Many modern wind turbine blades, such as the proposed 100m blade, have 2 or 3 shear webs to support blade mass and air-loads. Thus, avoiding blade design changes near the 3rd shear web region, and changing only near the trailing edge, there shouldn’t be too much effect on the blade structure. With this idea, the wavy pattern No. 1 modifications in geometry begin only after the 3rd shear web location. The flow comparisons between the primitive wavy design and the improved design airfoils have been discussed with details in section 5.1 of the current paper.

![Figure 2. Improved wavy trailing edge design](image)

3. Methodologies

The current research focuses on examining the changes in trailing edge vortex structures on the real scale SNL100-03 wind turbine blade [5] by employing the wave-trailing edge modification. Because wind turbine experiments on large real-scale blades are unrealistic due to their size, using CFD is especially valuable. However, because the complex trailing edge geometries on the blade create highly random vortex structures, this computation demands the use of a full 3-D Navier-Stokes solver rather than using simplified simulation techniques, such as Blade Element Momentum methods or lifting line methods. Thus, to resolve the complex geometry changes near the trailing edge, the Delayed Detached Eddy Simulation has been conducted with a modified laminar-turbulent transition model [6]. GPU-accelerated computation has been performed to reduce the massive computational costs [7]. In the current research, the GPU based FVM (Finite Volume Method) N-S solver, GPURANS3D developed at the University of Maryland has been used [7]. GPU computations have been conducted using the Deep-Thought II computer cluster located at the University of Maryland.

4. Research Objectives

In the current study, the main research objective is to reveal the effect of the wavy trailing edge modification on the real blade case. Before we test the full blade rotation, an 8meter length blade segment has been tested with common wind turbine operating conditions in the current setup. In the current research, the ‘SNL100-03’ blade, which was developed by Sandia National Labs in the United States, has been selected. The SNL100-3 blade has a flatback trailing edge on around 60%
of the blade. A blade segment located from 11.4 meter to 18.4 meter from the blade root has been selected (in Fig 3). The chosen segment has the most intensive transition of airfoil shapes among the whole blade sections. This is suitable to test the effect of the modified trailing edge on the irregular blade thicknesses. Blade modification details and modified airfoil shapes have been attached in the Appendix.

![Figure 3. The SNL100-03 Blade and the selected section for the current research](image)

5. Results

5.1 Validation and Previous results

A solver validation and previous research results are briefly presented, before explaining the main objective features and new findings of the current research. The primitive and improved design blade segments, which had been created, based on the baseline airfoils, ‘FB-3500-1700’ and ‘FB3500-0462’ rather than the real Sandia blade, had been tested to evaluate the solver accuracy and design characteristics. One of the pitfalls of wind turbine CFD might be the insufficient experimental data to be compared with computational result. However, there is sufficient wind tunnel experimental data, if one looks only at the 2D or quasi-3D blade segment data. For the SNL100-03 blade, there is well analysed data of the FB airfoil series produced by Baker and vanDam [1], which is eligible to be a simulation reference. The GPURANS3D had been validated by comparing with Baker and vanDam’s experimental data; presented in previous work [8].

In the previous setup, the two improved design patterns stated in section 2.2 were tested. The first pattern, ‘90C-3/4flatback-wavy’ is named from the modification length and the wave depth. Here ‘C’ stands for the airfoil chord length, and the ‘90’ means 90% of 1 chord length. Thus it means trailing edge had been modified only beyond 0.9C to the trailing edge. The second improve design pattern, ‘Halfway-cut-1/2flatback-wavy’ has been also named from its modification pattern. While the first pattern only modifies beyond 0.9C of the airfoil tail, the second pattern modifies a much longer region from maximum thickness location to the trailing edge; the same as the primitive design does. But, in the second pattern only the lower surface has been modified rather than modifying both the upper and lower surfaces. For this reason, the second pattern is named as ‘Halfway cut’. Briefly, both two wavy trailing edge modifications results in the same drastically reduced drag as compared to the previous wavy trailing edge designs while maintaining less loss of lift force for most testing angles of attack. This consequently enhanced the lift to drag envelope area shown in Figure 4. The vorticity magnitudes contours presented in Figure 5 show irregular shedding patterns along to the span-wise locations in both airfoil segments, rather than the strong span-wise Karman vortex roll ups of the typical flatback trailing edge. From the previous results, it looks like both improved designs work well as a drag mitigation device. However, considering the structural design concerns, the pattern No. 1 must be considered more realistic because of the shear web distribution in the blade.
Figure 4. Drag polar(left) and lift to drag envelope(right) from previous wavy trailing edge research

| Pattern#1. 90C-3/4 flatback wavy TE | Pattern#2. Halfway-1/2 flatback TE |
|-----------------------------------|-----------------------------------|
| Schematic Geometry                | Geometry                          |
| & Iso-Vorticity                   |                                   |

Figure 5. Comparison between two improved design patterns: vorticity magnitude fields

5.2 Aerodynamic Analysis

5.2.1 Mesh Generation. The SNL100-03 blade has been modified to be a span-wise wavy trailing edge at the inboard region of 11.4 meter (11.4% radius) to the 18.4 meter (18.4% radius) from the root. The wavy pattern No. 1 (90%C-3/4 flatback wavy TE) has been applied to the modification in the current research. Only the modified inboard region has been selected as a computational domain for both the original and modified cases. The computational meshes have been constructed with O-mesh topology around the local airfoil geometries and extruded along the blade span direction. The total mesh size of each segment is 213 x 101 x 101 (213 cells in the wrap around the airfoils, 101 cells in the normal to the blade surface direction, and 101 cells in the span-wise directions). Physical domain size is: 1.5C length to the span-wise direction, 50C length to the normal to the airfoil surface direction. The boundary condition of the blade surface has been
set as a viscous wall, and both of the sidewall boundaries have been treated as inviscid walls. A stretched mesh in the wall normal direction was used with an initial cell size at the wall of $\Delta y/C \sim 5 \times 10^{-6}$ ($y+ \sim 0.8$). The mesh has been presented in Figure 6.

![Blade segment mesh](image1)

**Figure 6. Blade segment mesh**

5.2.2 *Flow Conditions.* In the current study, the normal wind turbine operating state has been assumed. To setup inflow conditions, a blade rotation speed at the rated wind speed has been used. Rotation speed of common commercial wind turbines are usually 7~7.5 rpm at the rated wind speed. However, the SNL100-03 blade has been designed with optimum rotation speed of 9-9.5 rpm since it is much lighter than the previous blades. For that reason, the rotation speed has been set as 9.5 rpm in the current calculations. The incoming wind speed has been assumed as 13 m/s, and the rotation velocity profile has been set up as linear based on the optimum rotation speed and the local blade radius as shown in Figure 7. In the real blade rotation, the Reynolds number at the each blade span is different. However, in this case, the local Reynolds number $\sim 5,000,000$ has been assumed, since local variant of the chord lengths or the incoming flow is not too much different within the chosen blade segment region.

![Incoming flow conditions and velocity profile](image2)

**Figure 7. Incoming flow conditions and velocity profile**

5.2.3 *Computation Results.* Looking back to the previous results shown in section 5.1, the wavy trailing edge mitigates the aerodynamic drag forces dramatically while losing relatively small amount of lift forces, conclusively makes better aerodynamic performance. We expect similar aerodynamic benefit on the real wind turbine blade configurations in this section.

With the optimum turbine rotating conditions of the SNL100-03, the flow stream direction momentum ($\rho u$) contours of the original SNL100-03 blade, and the wavy modified blade segment are presented respectively in Figure 8. There are significant flow changes between the inboard and outboard locations. Observing the original flatback case result, there are massive flow separations at the thicker blade inboard regions, and it reaches almost to the thinner outboard regions. In the
wavy modified blade case result, the flow separations at the inboard regions also occurred, but it is much weaker than the original flatback case. For better understanding of the flow separation difference, x-plain sliced contours have been captured at the \( x/C \approx 0.9 \) in Figure 9. In Figure 9, stationary recirculation zones of the wavy modified blade behind looks like divided with three different regions, while the original flatback blade has one large stationary separation zone at the trailing edge. This verifies that the wavy pattern on the trailing edge interrupts span-wise coherency of the flow separation, by introducing stream-wise momentum at the each wave trough, and consequently holds up the flow separation comparing to the original flatback blade.

![Figure 8](image1.png)

**Figure 8. Stream-wise momentum contours**

![Figure 9](image2.png)

**Figure 9. Flow separation details: stream-wise momentum contours in x-slice captured at the \( x/C=0.9 \)**

By contrast, in the outboard region, the flow is well attached on the blade surface until very near the trailing edge in both blade sections. However, strong trailing edge vortex sheds with span-wise direction occurs on the original flatback blade. This can be observed clearly looking at the vorticity magnitude contours in Figure 10. It is clearly captured that the strong vorticity shows up continuously along the span direction at behind the trailing edge. However, the span-wise coherent trailing edge vortex no longer exists on the wavy modified blade. There are still strong vorticity regions behind the modified trailing edge, but they are more randomly distributed, and don’t have any coherency.
The local lift and drag forces have been plotted in Figure 11. At the inboard regions, local lift forces are less than 0.2 and drag forces are high, as much as 0.4, influenced by the massive flow separations. However, the lift gradually recovers as one approaches the outboard region. This is not so erratic when we recall the flow separation at the blade inboard. Some interesting feature of the plot is the lift forces of the wavy modified blade. The local Cl values of the modified blade are higher than the original blade at the flow separation region, but lower at the attached flow region. Furthermore, the drag forces of the modified blade are lower than the original blade all over the regions. And more drastic drag reductions are observed at the flow separation regions rather than at the blade outboard. This reminds us of the previous research results. In Figure 4, presented in the previous section, at high Angle of Attack (such as 16°~20°) there are more lift losses, but also even more drag reductions. In the previous cases, these were related to massive flow separations at the high Angle of Attack, and this is identical with the inboard separations of the current cases. The possible source of the massive flow separation at the inboard regions can be analogized as a drastic chord-wise variant of airfoil thickness. The current wavy modification rule only considers its trailing edge thickness rather than the maximum blade thickness. Thus, it must be valuable to add the parameter, ratio between maximum airfoil thickness and the trailing edge thickness, on to the current wavy modification rules.

(a) Original SNL100-03    (b) Wavy modified

Figure 10. Vorticity magnitude contours

Figure 11. Local lift and drag distributions along the span

5.3 Eigen Buckling Analysis

There might be concerns about structural uncertainties of the proposed wavy trailing edge design. In this chapter, structural characteristics of the wavy modified 100-m blade have been discussed. The modified blade geometry and numerical solver input parameters have been created using NuMad software, which has been developed by Sandia National Lab. NuMad model geometries
of the original SNL100-03 flatback blade and the wavy modified blade are shown in the Figure 12. The same modified region and wave shape with the aerodynamic simulations have been applied to the structural analysis model. The Ansys APDL (Ansys Parametric Design Language) mechanical solver has been used for the current study. The aerodynamic force loadings on the blade model have been mapped as presented in the Figure 13. The two lines of forces have been applied on the blade. Normal forces acting on the rotation plane have been applied on the spar cap where the shear web locates, and tangential forces acting on the rotation plane have been applied on the leading edge of the blade. The aerodynamic forces have been calculated using Aerodyn V15, the BEMT (Blade Element Momentum Theory) solver developed by Sandia National Lab. In the analysis, the blade rotation speed assumed as 9.5 rpm, and the incoming wind speed set as 11.4 m/s. The open source original SNL100-03 model file has been used in the current study, and the turbine operation conditions have been set as much as same with Griffith’s research [5]. Thus, as a reference, for the original SNL100-03 blade case, we only tried to duplicate his buckling result in the study.

Eigen buckling analysis results have been presented in Figures 14 and 15. The lowest mode buckling results of the two blade models are nearly identical to each other, and also identical with Griffith’s results. Both the original SNL100-03 and the modified blade buckle at the blade outboard of mid span region, where the third shear web ends. Nonetheless, despite concerns of the structural failure at the wavy modified area, no significant buckling failure at the wavy modified region has been observed in the current study.

![Figure 12. Spanwise wavy trailing edge modification of the SNL100-03 blade NuMad model](image)

![Figure 13. Normal and tangential line force loading on the SNL100-03 blade](image)
6. Conclusions
The span-wise wavy trailing edge design has been applied to the brand new Sandia 100meter blade, SNL100-03 Flatback. Since previous tests had been conducted with the wind tunnel operating conditions and geometries, in the current research, the simulations of the real blade geometry with the wind turbine operating flow conditions have been tried. An 8meter-length blade segment among an inboard section of the full SNL100-03 blade has been chosen for the current simulations, and trailing edge is modified with the wavy pattern No. 1 (90%C-3/4flatback wavy). A total of 6 wave paves have been created on the blade segment trailing edge. With the optimum blade rotating conditions, the flow separated massively at the thick inboard region. However, the modified blade reduced the flow separations as compared to the unmodified blade by catalyzing stream-wise momentum through the spanwise wave geometries. There was some lift loss at the
outboard region and lift recovery at the inboard; however, the drag is reduced all over the regions. Thus, overall the wavy trailing edge modification will have a positive effect on the power generation of the turbine. Therefore, the positive effect of the wavy trailing edge modification on the real wind turbine blade has been proven by the current results. However, the drag reduction with the wind turbine operating flow conditions was less than with the wind tunnel cases, because of the relatively slow incoming air flow. For this matter, it might be valuable to consider the deeper wave depths on the trailing edge for the real wind turbine conditions. From the simple Eigen buckling analysis results, it is verified that the wavy modification with improved design (very small changes of the trailing edge) doesn’t affect the blade structural reliability.

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7. References
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