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Effects of Wavy Leading Edge on the NREL Phase VI Wind Turbine Annual Performance

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Abstract. *The current global economy is sustained by fossil fuels, which have increased the greenhouse emissions that contribute to the global temperature increase. Renewable energy sources have the potential to mitigate these gas emissions; however, its capacity extension faces the energy trilemma that involves energy security, energy equity, and environmental sustainability. To overcome this trilemma, governmental policies are as important as the technological development. The Wavy Leading Edge (WLE, also known as leading edge protuberances) is a passive control flow device that enhances the aerodynamic performance at high angles of attack. When implemented on the NREL Phase VI wind turbine blade, it increases the blade torque only at high wind speeds ($\geq 15\ m/s$) and degrades it at the blade design wind speed ($10\ m/s$). However, the parameters used to design the WLE have been limited to the wave amplitude and wavelength. When the WLE size is designed proportional to the blade chord and the wave asymmetry parameter is included, its torque can be less severe degraded at the the blade design wind speed and still increased at higher wind speeds. In this study, the effects of these design parameters on the blade torque were used to assess its annual power output variation. The Weibull distribution was used to calculate the wind distribution and density at three different main wind speed ($\overline{U}$) values: 7.5, 10 and $12.5\ m/s$. Two shape factors were considered, to have a distributed wind density probability and a sharpened one. It was found that all blades degrade the blade annual power output performance at $\overline{U} = 7.5\ m/s$, specially if the wind density probability concentrates at lower wind speeds. At $\overline{U} = 10\ m/s$, some WLE configurations enhance the blade performance when the wind density probability is not sharpened. The asymmetrical WLE blade out stands with 6.2% performance increase. At $\overline{U} = 12.5\ m/s$, almost all WLE configurations enhance the blade performance for both shape factors. As shown, the same blade with different WLE configurations can have its annual performance increased for specific environmental conditions; therefore, the WLE device has the potential to increase the wind energy harvesting and contribute to the energy transition towards renewable energies.*

Keywords: *Wind Energy, Leading Edge Protuberances, WLE, NREL Phase VI Wind Turbine, Biomimetics*

1. Introduction

The concern on the greenhouse gas emissions and their effects on the average global temperature increase has increased over the last decades. Since the fossil fuel energy generation sustains the current global economy and is the main source of CO_2 emissions, the awareness for the need of sustainable clean renewable energies has also increased. In 2019, renewable energies have covered as much as 25% of the global primary energy consumption, being bio-energy and hydroelectricity the ones with the largest share with approximately 10% and 7% of the total primary global energy supply (REN21, 2019). Although wind and solar energy still represented a low percentage of the global total energy supply, they are world wide available abundant clean sources of energy. Further more, wind energy stands as one of the most cost-effective and sustainable energy sources. Diverse countries have deployed wind farms to their national energy grid to replace fossil fuels (Msigwa *et al.*, 2022). Nevertheless, the transition from fossil fuel energy generation to renewable energy sources face diverse challenges regarding governmental policies and its technological development to overcome the energy trilemma that involves energy security, energy equity, and environmental sustainability (Werner and Lazaro, 2023; Council, 2022).

China, the USA an India were the countries with the largest global CO_2 emissions in 2021 with 32.9%, 12.6% and 7.0% respectively (Crippa *et al.*, 2022). However, those are the countries with the largest renewable energy capacity expansion expectation between 2022 and 2027 (almost 75%), driven by the implementation of existing policies and regulatory and market reforms (Agency, 2022). Brazil CO_2 emissions represent only 1.3% of the global emissions; nevertheless, its electricity expansion plans emphasize on wind and solar photovoltaic among the renewable energy sources. The public incentives and credit policies are a key aspect for the alternative energy market consolidation (Crippa *et al.*, 2022; **?**).

The Wavy Leading Edge (WLE), also known as leading edge protuberances, is a passive control flow device inspired on the leading edge bumps of the Humpback whale pectoral flippers (see Fig. 1). Those bumps create counter-rotating vortices on the chord-wise that increases the flipper hydrodynamic performance at high angles of attack, smooths stall and increases lift after the regular stall angle(Fish and Battle, 1995; Miklosovic *et al.*, 2004; Custodio, 2007).

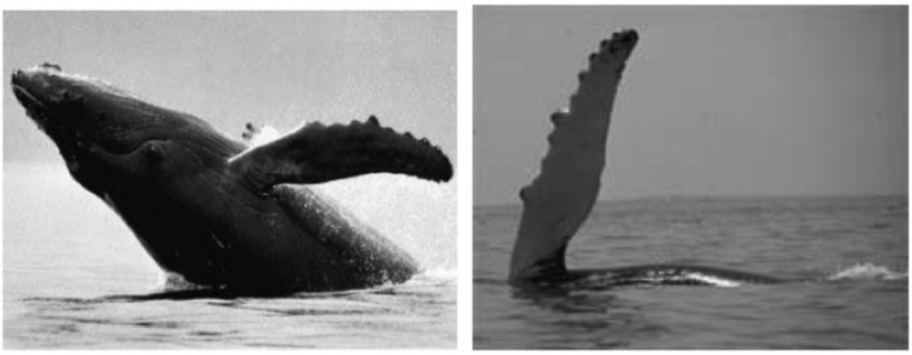

Figure 1: Humpback whale jumping out of water and pectoral flipper detail (Johari *et al.*, 2007).

The effects of the WLE are determined by its governing parameters, amplitude (A) and wavelength (λ). Amplitude increment smooths stall and increases lift at the stall regime; however, it can also degrade the lift slope and maximum lift. λ reduction helps to smooth stall and tends to increase lift performance before stall and maximum lift; still, it has smaller effects than A (Johari *et al.*, 2007; Hansen *et al.*, 2011). WLE asymmetry and wave size in function to the local chord were studied as additional WLE design parameters. WLE asymmetry (see Fig. 2) has shown potential to enhance or reduce the span-wise flow and wing tip vortex intensity, according to its asymmetry direction (Mezarina *et al.*, 2019). WLE size proportional to the local chord leads to even effects along the span when there is taper ratio (Flores-Mezarina *et al.*, 2021, 2023).

(a) Symmetrical WLE (b) Asymmetrical WLE

Figure 2: Reference: Mezarina *et al.* (2019)

The horizontal axis wind turbines (HAWT) are designed to operate at the most probable wind speed (u). Since high wind speeds can endanger them, a blade twist angle is used in the passive control mechanism to induce stall gradually from the blade root towards its tip. This type of blades are exposed to stall and deep stall operational conditions(Manwell *et al.*, 2010). The WLE could be used to enhance this blades' performance, since it enhances wings aerodynamic performance at the stall regime.

The NREL Phase VI wind turbine blade is designed with a single airfoil (S809), linearly decreasing chord, and twist angle variation that fits to a polynomial function. These features make it a suitable blade to study the WLE effects on wind turbines and torque generation. It was found that the blade torque performance is increased by the WLE only at high improbable wind speeds ($u >= 15\ m/s$) and its degraded at the blade design wind speed ($u = 10\ m/s$) by as much as 23% or 50%, or only by 13% or 8.5% according to the A and λ configurations and to designing the WLE size constant to a chord value or to the blade local chord (Zhang and Wu, 2012; Abate *et al.*, 2019; Flores-Mezarina *et al.*, 2021).

Since wind incidence and behaviour changes according to the geography and time of the year. The Weibull statistical distribution is commonly used to forecast wind speed and density, so its is used on assessing wind energy potential. In this study, the Weibull distribution is used to assess the effects of the WLE on the annual energy production of the NREL Phase VI wind turbine blade. The parameters assessed for the WLE design are A, λ, WLE size according to a fixed or local chord, and WLE asymmetry.

2. Methodology

2.1 Geometry

In addition to the set of five blades built to assess the effects of designing the WLE in function to a fixed chord value or to the blade local chord (Flores-Mezarina *et al.*, 2021), a blade with WLE size proportional to the blade local chord and asymmetrical WLE set towards the blade root was built (see Fig. 3). The blades nomenclatures and parameters are shown in table 1.

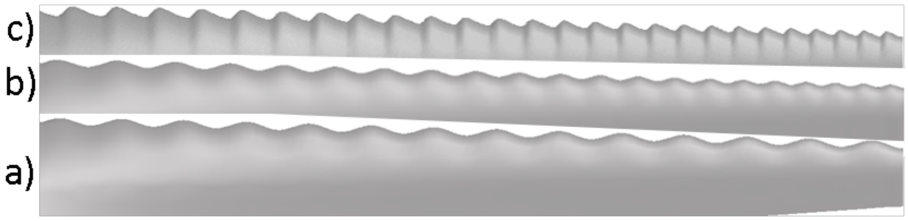

Figure 3: Comparison of the NREL wind turbine blade leading edge built with the WLE size constant to a fixed chord value (a), proportional to its local chord (b) and, proportional to its local chord and asymmetrical WLE (c).

Blade	At the blade Root		At the blade Tip		**Symmetric?**
	A	λ	A	λ	
NREL	-	-	-	-	-
N-rt1	4.5	43	9.3	88.5	Yes
N-rt2	2.1	30	4.3	61.8	Yes
N-loc1	4.5	43	4.5	43	Yes
N-loc2	2.1	30	2.1	30	Yes
N-loc3-a	3.0	27	3.0	27	No

Table 1: Blades tested and their A and λ ratios at the blade root and tip as percentage of the local chord. Blades N-rt1 and N-rt2 have the WLE size constant to a fixed chord value; blades N-loc1, N-loc2 and N-loc3-a have it proportional to its local chord. Blade N-loc3-a has asymmetrical WLE.

2.2 Numerical Analysis

As for the set of five blades tested on the previous study, the numerical analysis for the asymmetrical one was performed on the finite element based commercial software ANSYS® CFX solver. An static external domain and a internal rotating sub-domain both composed by unstructured tetrahedral elements were used. Only the 25 fist layers over the blades were structured and small enough to reach $y+ \approx 1$. Domain and sub-domain boundary condition was set as frozen-rotor general grid interface. Due to its overall little lift, drag and momentum error, the k-! SST turbulent model was used in the solver (Menter *et al.*, 2003). Only the wind turbine blades were simulated.

2.3 Wind Distribution / Weibull dist

To assess the turbine's annual energy production, three different mean wind speeds ($\overline{U}$) were considered on the Weibull distribution: 7.5, 10 and 12.5 m/s; and two shape factors (k): 2 and 4. These shape factors created two wind density probability ($P(U)$) profiles, the first one distributed around $\overline{U}$, while the second one is sharpened and concentrates $P(U)$ near $\overline{U}$. The cases contemplated, their parameters, and the resulting $P(U)$ are shown in Tab. 2.

$\overline{U}$ [m/s]	7.5		10		12.5	
Case	C1	C2	C3	C4	C5	C6
k	2	4	2	4	2	4
c	8.5	8.3	11.3	11.0	14.1	13.8
u [m/s]	P(U) %					
5	9.8	9.3	6.5	3.2	4.4	1.4
10	6.9	10.1	7.2	13.7	6.1	8.4
15	1.8	0.0	4.0	3.0	4.9	9.2
20	0.2	0.0	1.4	0.0	2.7	1.1

Table 2: Weibull distribution and probability density for the studied wind speeds.

3. Results

3.1 Torque

Figure 4 shows the effects of the WLE on torque. All WLE blades degrade torque at u = 10 m/s and enhance it at higher wind speeds. As seen at the previous study, the WLE size set constant to a fixed chord value or proportional to the blade chord has the potential to increase the blade torque performance at u = 15 m/s and u = 20 m/s by as much as 22 and 25%, and to degrade it by as low as 7% at u = 10 m/s, according to its A and λ parameters. Nevertheless, the blade with asymmetrical WLE degraded torque at the u = 10 m/s by 10% and increased it at u = 15 m/s and u = 20 m/s by as much as 27 and 36%.

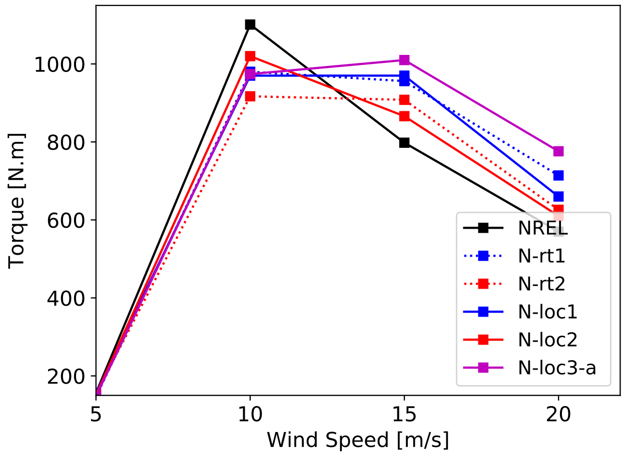

Figure 4: Effects of the WLE on the NREL Phase VI Wind Turbine performance under the diverse approaches.

3.2 Annual Power Output

Table 3 shows the annual power output of each blade at each wind mean velocity ($\overline{U}$) considered on table 2 and its comparison to the base NREL blade. At $\overline{U}$ = 7.5 m/s all the WLE configurations degrade the blade performance, which was expected since the WLE is effective only at stall regime. The blade that performs the worst is N-rt2, which is the blade that degrades torque at u = 10 m/s the most (almost 17%). Although blade N-loc3-a has not the best torque performance at u = 10 m/s, it is the blade that has the lower performance degradation at the same u for k =2, 2.2%. At $\overline{U}$ = 10 m/s, blades N-rt1, N-loc1 and N-loc3-a enhance the blade performance for k =2, by 3.1, 2.2 and 6.2% respectively. However, all WLE configurations degrade the blade performance for k =4 by as much as nearly 11%. Finally at $\overline{U}$ = 12.5 m/s almost all WLE configurations enhance the blade performance at both k values. Blade N-loc3-a out stands with as much as 11.8% of performance enhancement.

Blade	Annual Power Output [MWh]					
Case	C1	C2	C3	C4	C5	C6
NREL	9.4	10.4	12.9	16.6	14.0	18.9
N-rt1	9.1	9.3	13.3	15.8	15.0	20.2
N-rt2	8.6	8.7	12.5	14.8	13.9	19.0
N-loc1	9.1	9.2	13.2	15.7	14.8	20.2
N-loc2	9.1	9.6	12.8	15.9	14.1	19.2
N-loc3-a	9.2	9.2	13.7	15.9	15.6	20.9
Blade	Δ% Power Output vs NREL					
N-rt1	-3.6	-10.6	3.1	-5.2	7.4	6.8
N-rt2	-9.0	-15.9	-3.5	-10.8	-0.2	0.4
N-loc1	-4.0	-11.4	2.2	-5.5	5.8	6.8
N-loc2	-3.6	-7.1	-0.5	-4.4	1.3	1.5
N-loc3-a	-2.2	-11.0	6.2	-4.3	11.8	10.6

Table 3: WLE blades Annual Power Output and its variation compared to the base NREL blade.

4. Conclusions

The transition from fossil fuel energy generation to the use of renewable sources of energy to reduce the CO_2 emissions is driven by governmental policies and incentives, and technological development that enables energy generation from renewable sources as solar photovoltaic and wind energy. In this study, the NREL Phase VI wind turbine blade was used to assess the effects of the Wavy Leading Edge (WLE) on its annual power output. The WLE is a passive control flow device that enhances aerodynamic performance at the stall regime. When tested on horizontal axis wind turbine blades, it improves the blade torque generation only at high wind speeds. When the approach on the WLE design is limited to variate the WLE A and λ parameters and the WLE size in function to a fixed chord value instead of considering the blade local chord, the WLE performance effects are also limited. Introducing the asymmetry parameter on the WLE design has shown potential to increase the blade performance at high wind speeds without a major performance cost at the blade design wind speed. Although it seems that its applications in wind turbine blades are limited to high improbable wind speeds, the assess of the annual power output has show that WLE can improve the blade performance according to the annual wind distribution and density. Therefore, blades with different WLE configurations could improve its performance at different environmental conditions without any major design variation, which can contribute to enhance the wind energy harvesting and accelerate the transition to the use of renewable energy.

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