Effects of Leading Edge Erosion on the Power Performance and Acoustic Noise Emissions of Locally Manufactured Small Wind Turbine Blades

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Abstract. The local manufacturing of small wind turbines has become increasingly popular over the last decade, among international networks of renewable energy practitioners, for the implementation of rural electrification applications. Locally manufactured small wind turbines (LMSWTs), used most frequently in off-grid battery based renewable energy systems, typically utilize wooden blades and coreless axial flux permanent magnet generators due to their simple manufacturing process and local availability of materials. In this paper the effects of leading edge erosion on locally manufactured small wind turbine blades are researched experimentally, both in terms of power performance and acoustic noise emissions. From the research it is concluded that a yearly maintenance of the wooden blades of a LMSWT can lead to less acoustic noise emissions and better power performance, with the latter becoming more significant as the mean wind speed of the installation site increases. For practitioners, installers and manufacturers of LMSWTs, these findings can significantly guide manufacturing processes and techniques in terms of preventing leading edge erosion, while also advising preventative maintenance procedures on the field, in order to keep small wind electric systems quiet and productive.

1. Introduction
Since their introduction in 2015, the UN Sustainable Development Goals (SDG) target social and economic issues, with SDG No7 focusing on the universal access to sustainable and affordable energy. In this aspect, low cost renewable energy technologies contribute to the increase of small scale electricity production for remote areas and make such systems more accessible to rural communities. In particular the local manufacturing of such technologies significantly reduces capital costs, with the use of locally available materials, tools and manufacturing techniques, and further reduces maintenance costs [1] by providing the necessary socio-technical environment with appropriate training of the user community.

A widespread technology with such characteristics is locally manufactured small wind turbines (LMSWTs) [2]-[6] (Fig.1). Several design manuals [7] and on-line tools [8] have been a reference guide for LMSWTs, with an increasing number of NGOs, technical groups and practitioner networks implementing them on the field, in order to locally manufacture small wind turbines for the electrification of rural communities in developing countries. International practitioner networks such
as the Wind Empowerment association are actively promoting the technology of LMSWTs, counting several hundreds of installations on all continents and a growing user community.

![Image](image_url)

**Figure 1.** Local manufacturing of wooden blades using hand tools and an installed 2.4m rotor diameter locally manufactured small wind turbine [3].

LMSWTs are most frequently used in wind/solar hybrid off-grid systems, of installed generation capacity of up to 10kW. Rotor diameters span from 1.2m to 6m, respectively producing power from 200W to 5kW at a 10m/s wind speed. They are variable speed machines, consisting of a three blade wooden [9]-[10] horizontal axis rotor of constant pitch angle, of a coreless axial flux permanent magnet generator [11] with a double rotor single stator configuration and use a passive gravity furling tail system for rotor speed regulation.

In this paper, the effects of leading edge erosion on locally manufactured small wind turbine blades are researched experimentally in terms of power performance and acoustic noise emissions, with the aim of informing preventative maintenance procedures planed by practitioners, installers and manufacturers of LMSWTs. As such procedures are embedded in the socio-technical ecosystem [12] of the installations, quite operation and enduring power production can significantly contribute towards the sustainability of such systems. Additionally, this paper aims at contributing to relevant research on the effects of leading edge erosion [13] on various aspects of wind turbine technology such as rotor power performance [14] and annual energy production [15], optimal aerodynamic coefficient $c_{\text{opt}}$ and tip speed ratio $\lambda_{\text{opt}}$ [16]-[17], and field measurements of acoustic noise emissions [18]-[19], while at the time expanding the limited literature on these themes [20]-[21] with reference to small wind turbines.

2. Experimental facilities

2.1. Field testing facility and experimental setup

A 2.4m rotor diameter LMSWT, delivering 600W of rated power at a 11m/s wind speed, was tested on a 12m guyed tower while connected directly to a 48VDC battery bank, at the NTUA small wind turbine test site in the coastal region of east Attiki. Meteorological and electrical measurements were performed with appropriate sensors, while all power performance measurements and calculations were conducted in accordance with the relevant IEC standard [22] for measuring the performance of wind turbines, and specifically Annex H which refers to small wind turbine testing.
 Furthermore, all acoustic noise measurements were conducted in accordance with the relevant IEC standard [23] on acoustic noise measurements for wind turbines. The microphone and sound level meter were placed on a flat rock surface with rounded edges downwind from the prevailing wind direction (Fig. 2) and at a horizontal distance of 12.5m from the tower base.

Two sets of 2.4m blade rotors were tested at the test site for power performance and acoustic noise emissions, namely a recently manufactured rotor with a smooth airfoil and a used rotor with eroded leading edges from rain and dust. The used rotor had not been maintained for a period of 18 months and was used in a highly erosive coastal environment.

2.2. Wind tunnel testing facility and experimental setup

Two scaled down versions of locally manufactured wooden rotors were tested in the wind tunnel of the laboratory of aerodynamics of the NTUA (Fig. 3), namely two rotors of 1.2m in diameter, one with smooth and one with eroded leading edges. The mechanical torque on the shaft was measured using a rotary torque sensor, while the appropriate rotational speed of the rotor was provided by a variable speed DC motor drive and the wind tunnel wind speed was varied from 3m/s to 11m/s. The experimental setup was arranged so as to provide a complete range of tip speed ratio values for the rotors under test, for the complete wind speed range of the wind tunnel.

Figure 2. (a) Hand held sound level meter measuring position and (b) leading edge erosion of wooden locally manufactured blade.

Figure 3. A wooden locally manufactured rotor in the wind tunnel of the NTUA.
3. Acoustic noise emissions

Initially, the site conditions for acoustic noise measurements were assessed. All valid data points for the sound pressure levels of wind turbine with smooth rotor and background noise emissions, for wind speeds from 4m/s to 10m/s, are shown in Fig.4. Wind turbine noise measurements display adequate separation from those of background noise, thus verifying that the test site provides a good experimental set up for acoustic noise measurement of this type.

Measurements of the sound pressure level of the smooth and eroded rotors against background noise, are displayed in Fig.5. A wide range of wind speeds, from 4m/s up to 10m/s, have produced valid measurement data points according to [23], allowing for the observation of blade erosion induced noise emissions for a range of both low and high wind speed modes of rotor operation.

Inflow-turbulence noise on a blade is caused by the interaction of the upstream atmospheric turbulence with the leading edge of the blade [24], so the eroded rotor is expected to operate with higher noise emissions. As observed in Fig.5, the acoustic noise emissions of the eroded rotor blades are increased by an average of 10% (or 4 dBA) for the whole range of wind speeds from 4m/s up to 10m/s. Individual increases in sound pressure levels for each wind speed are shown in Table 1, were a more severe influence of leading edge erosion on acoustic noise emissions can be observed for operation at higher wind speeds, in particular above 7m/s.

![Figure 4](image1.png)

**Figure 4.** Sound pressure level data points of the small wind turbine with the smooth rotor against background noise for various wind speeds.

![Figure 5](image2.png)

**Figure 5.** Processed sound pressure level data of the eroded and smooth small wind turbine rotors against background noise for various wind speeds.
Table 1. Sound pressure levels per wind speed, corrected for background noise, for the smooth and the eroded rotors.

| Wind Speed (m/s) | Background (dBA) | Eroded Rotor (dBA) | Smooth Rotor (dBA) | SPL Difference (dBA) |
|------------------|------------------|---------------------|---------------------|----------------------|
| 4                | 28.30            | 41.20               | 38.36               | 2.84                 |
| 5                | 29.79            | 43.50               | 39.70               | 3.80                 |
| 6                | 32.87            | 46.30               | 42.10               | 4.20                 |
| 7                | 35.57            | 48.91               | 44.40               | 4.51                 |
| 8                | 38.63            | 50.86               | 46.21               | 4.65                 |
| 9                | 41.97            | 52.54               | 46.95               | 5.59                 |
| 10               | 44.27            | 53.36               | 47.20               | 6.16                 |

Furthermore, this increase of acoustic noise emissions due to leading edge erosion, shifts the acoustic noise performance of the small wind turbine further away from the acceptable noise limits for residential areas in open country, which are 44 dB for wind speeds of 8 m/s and 42 dB for wind speeds of 6 m/s, according to Danish noise level limits [25] for installation of wind turbines.

4. Power performance

Power performance measurements were conducted both in field tests and in wind tunnel tests in order to observe different aspects of leading edge erosion on locally manufactured wooden rotors.

4.1. Field tests

The power performance of the smooth and eroded small wind turbine rotors is investigated further at the test site, with the resulting power curves displayed in Fig.6. A significant reduction in rated power production can be observed for wind speeds close to the rated. Specifically a reduction of 23.7% is noted at the rated wind speed of 11m/s, while similar reductions in power production are evident for all wind speeds above 10m/s. On the contrary, for wind speeds below 7m/s, the power performance of the eroded rotor remains similar with that of the smooth rotor. In the last part of this section, this increase in performance of the eroded rotor is investigated further, while the wind tunnel tests of the next section provide additional experimental data on this matter.

Figure 6. The power curves for the smooth and the eroded small wind turbine rotors under field testing.
The above results become more evident when considering the overall system efficiency $C_p$ of the wind electric system, as displayed in Fig. 7. For wind speeds higher than 6.5 m/s, and especially close to the rated wind speed, the efficiency of the system is significantly reduced due to leading edge erosion, with values of up to 23.6% at the rated wind speed, specifically a reduction of efficiency from 0.154 to 0.117. Yet for lower wind speeds, i.e. from 3.5 m/s up to 6.5 m/s, the system efficiency of the eroded rotor displays a similar performance to that of the smooth rotor. Particularly at 5.5 m/s there is a system efficiency increase of the eroded rotor of 2.3%, specifically an increase of efficiency from 0.305 to 0.312.

**Figure 7.** The system efficiency $C_p$ for the smooth and the eroded small wind turbine rotors under field testing.

The influence of leading edge erosion on the Annual Energy Production (AEP) of the wind electric system is further investigated, with the results displayed in Fig. 8. The similar power performance at low wind speeds between the eroded and smooth rotors which was observed in previous graphs, makes the influence of leading edge erosion of the blade rotor less pronounced in the AEP for lower mean wind speeds. As seen in Table 2, specifically for mean wind speeds from 4 m/s to 6 m/s the reduction in AEP gradually increases from 0.1% up to 9.6%.

**Figure 8.** The Annual Energy Production (AEP) for the smooth and the eroded small wind turbine rotors under field testing.

For wind turbines of class IV or specifically for small wind turbines, which are installed closer to the ground with common hub heights ranging from 6 m up to 24 m, installation sites with mean wind speeds of 4 m/s to 6 m/s are the most frequent. From the above results it can be concluded that the
reduction in AEP for LMSWTs due to blade leading edge erosion will be more significant as the mean wind speed of the site increases from 4m/s to 6m/s, which emphasizes the need for more strict preventative maintenance planning in sites with higher mean wind speeds.

**Table 2.** Annual Energy Production (AEP) per mean wind speed, including measurement uncertainty $u_{\text{AEP}}$, for the smooth and the eroded rotors.

| Wind Speed (m/s) | AEP Smooth Rotor (kWh) | $u_{\text{AEP}}$ Smooth Rotor (%) | AEP Eroded Rotor (kWh) | $u_{\text{AEP}}$ Eroded Rotor (%) | AEP Difference (%) |
|-----------------|------------------------|-----------------------------------|------------------------|-----------------------------------|-------------------|
| 4               | 713                    | 10.1                              | 713                    | 9.6                               | 0.1               |
| 5               | 1247                   | 8.1                               | 1181                   | 7.3                               | 5.3               |
| 6               | 1782                   | 6.6                               | 1610                   | 5.9                               | 9.6               |
| 7               | 2252                   | 5.6                               | 1957                   | 4.9                               | 13.1              |
| 8               | 2624                   | 4.9                               | 2204                   | 4.4                               | 16.0              |
| 9               | 2891                   | 4.4                               | 2352                   | 4.0                               | 18.7              |
| 10              | 3057                   | 4.0                               | 2413                   | 3.8                               | 21.1              |
| 11              | 3133                   | 3.8                               | 2406                   | 3.7                               | 23.2              |

In the last part of this section, the slight increase in performance of the eroded rotor in lower wind speeds is investigated further. This is traced back to an operation of the eroded rotor closer to the optimal tip speed ratio $\lambda_{\text{opt}}$ of the blades.

LMSWTs operate in low cost and low complexity wind electric systems in order to comply with the requirements of remote rural electrification applications, where maintenance and capital costs need to be low. For this reason, locally manufactured wind energy conversion systems do not perform maximum power tracking, either with varying the blade pitch angle or with the use of power electronics. Consequently, the tip speed ratio that the rotor of a LMSWT has a fixed relationship with wind speed, as seen in Fig. 9, and is mostly dependant on the electrical loading of the wind turbine generator.

**Figure 9.** Differences in the tip speed ratio (TSR) of two rotors under test due to leading edge erosion.

It can be observed that for wind speeds up to 7m/s, both the smooth and the eroded rotors operate at tip speed ratios higher than the optimal, which is about 5, as can be seen in the wind tunnel tests of the next section. The eroded rotor operates at a slightly lower TSR for all wind speeds, due to the stalling effect of higher drag forces due to leading edge erosion. Yet, this brings the operation of the eroded rotor slightly closer to its optimal TSR, particularly in low wind speed range below 7m/s, and as a result the loss in blade efficiency due to leading edge erosion is mitigated. For wind speeds above
7m/s the tip speed ratio of both rotors is lower than the optimal, which brings the blades into their stall region of operation, and so the previously mentioned effect ceases to occur. Further insight into this phenomenon is provided in the next section with the assistance of wind tunnel tests performed on the two rotors.

4.2. Wind tunnel tests

The aerodynamic performance of the locally manufactured rotors is investigated in wind tunnel tests, measuring experimentally the aerodynamic coefficient over a wide range of operating points, spanning a series of tip speed ratios and wind speeds. In addition, the effects on aerodynamic performance of leading edge erosion of wooden locally manufactured blades are investigated further.

The effect of operation at low Reynolds number can be seen in the experimental results of Fig. 10, with Reynolds numbers varying from $7 \times 10^4$ at 3m/s up to $1.7 \times 10^5$ at 10m/s in the optimum tip speed ratio $\lambda_{opt}$ region. It can be observed that the optimal value of the aerodynamic coefficient $c_{p, opt}$ for the smooth rotor starts at values of 0.29 at 3m/s and rises rapidly to 0.33 at 7m/s, while staying stable until 10m/s. For the eroded rotor the optimum values of the aerodynamic coefficient $c_{p, opt}$ start at lower values of 0.25 at 3m/s and rise up to 0.32 at 7m/s, while staying stable until 9m/s after which there is slight decrease. Overall, the eroded rotor reaches a lower optimal aerodynamic coefficient than the smooth rotor by about 7%, a difference of 0.024 at rated power. With respect to the optimum value of the tip speed ratio $\lambda_{opt}$ it shifts from higher values of about 6 for low wind speeds to lower values of about 5 for higher wind speeds. The results for the wind tunnel measurements of $c_{p, opt}$ and $\lambda_{opt}$ can be seen in detail in Table 3.

![Figure 10. The aerodynamic coefficient of locally manufactured rotors, (a) without erosion and (b) with erosion, as measured in the wind tunnel.](image-url)

As observed in the experimental results of Fig.10, the maximum value of the aerodynamic coefficient is influenced to an extent due to leading edge erosion. Additionally, it can be observed that for the eroded rotor the shape of the $c_p-\lambda$ curves per wind speed remains the same for tip speed ratios above the optimal, while for tip speed ratios below the optimal $c_p$ values drop drastically when compared with the smooth rotor. As a result, when the eroded rotor operates in tip speed ratios above the optimal, the values of the aerodynamic coefficient are reduced to a lesser extent when compared to the smooth rotor, than when operating below the optimal tip speed ratio.
The increased performance of the eroded rotor at low wind speeds, as analysed in the previous section, is such a case. As seen in Fig. 9, the eroded rotor operates at tip speed ratios above 5 for wind speeds of up to 7 m/s, and as seen in Fig. 10, this reduces only slightly the power performance of the eroded rotor. Additionally, the operation of the smooth rotor at slightly higher tip speed ratios and at slightly lower values of aerodynamic coefficient \( c_p \), for the same wind speed range, results in a similar power performance between the two rotors. Above 7 m/s, the eroded rotor operates below the optimal values of tip speed ratio and enters into the stall region of the \( c_p - \lambda \) curves, thus significantly reducing the values of \( c_p \). For the smooth rotor, this happens at about 10.5 m/s, which accounts for the better power performance of the smooth rotor at higher wind speeds.

### Table 3. The optimal values of the aerodynamic coefficient \( c_{opt} \) and of the tip speed ratio \( \lambda_{opt} \) as measured in the wind tunnel for the smooth and the eroded rotors.

| Wind Speed (m/s) | Reynolds Number | Aerodynamic Coefficient \( c_{opt} \) | Tip Speed Ratio \( \lambda_{opt} \) | Aerodynamic Coefficient \( c_{opt} \) | Tip Speed Ratio \( \lambda_{opt} \) |
|-----------------|----------------|----------------------------------|----------------------------|----------------------------------|----------------------------|
| 3               | 6.8 x 10^4     | 0.291                            | 6.55                       | 0.253                            | 6.13                       |
| 4               | 7.8 x 10^4     | 0.322                            | 5.67                       | 0.291                            | 6.10                       |
| 5               | 8.9 x 10^4     | 0.327                            | 5.15                       | 0.304                            | 5.48                       |
| 6               | 1.05 x 10^5    | 0.329                            | 5.06                       | 0.311                            | 5.20                       |
| 7               | 1.15 x 10^5    | 0.333                            | 4.79                       | 0.315                            | 5.01                       |
| 8               | 1.26 x 10^5    | 0.333                            | 4.55                       | 0.316                            | 4.95                       |
| 9               | 1.46 x 10^5    | 0.333                            | 4.73                       | 0.318                            | 4.73                       |
| 10              | 1.68 x 10^5    | 0.335                            | 4.84                       | 0.311                            | 4.84                       |

5. Conclusion

In this paper the effects of leading edge erosion on locally manufactured small wind turbine blades are researched experimentally, both in terms of power performance and acoustic noise emissions. Acoustic noise emissions of eroded rotor blades are found to increase by an average of 10% (or 4 dBA) over smooth blades for a range of wind speeds from 4 m/s up to 10 m/s, with the influence becoming more significant at higher wind speeds. A reduction of power production of up to 23.7% and of system efficiency from 0.154 to 0.117 are observed for the eroded rotor at the rated wind speed. On the other hand, for lower wind speeds from 4 m/s up to 6 m/s, the system efficiency of the eroded rotor displays similar performance to that of the smooth rotor. This behaviour of the eroded rotor at low wind speeds is traced back to its operation closer to the optimal tip speed ratio \( \lambda_{opt} \) of the blades, due to stalling caused from the erosion of the leading edge. With respect to the AEP, for mean wind speeds from 4 m/s to 6 m/s the reduction in AEP gradually increases from 0.1% up to 9.6%. Wind tunnel tests show the behaviour of the smooth and the eroded rotors for low Reynolds numbers, concluding that the maximum value of the aerodynamic coefficient is reduced due to leading edge erosion by about 7% at rated power, yet this reduction is compensated for wind speeds below 7 m/s, due to the operation of the eroded rotor closer to its optimal tip speed ratio due to increased stalling.

From the experimental results of the paper, it can be concluded that a yearly maintenance of the wooden blades of a LMSWT, which includes smoothing the airfoil and repairing the leading edge, can lead to less acoustic noise emissions and better power performance, with these aspects becoming more significant as the mean wind speed of the installation site increases. For practitioners, installers and manufacturers of LMSWTs these findings can significantly guide their manufacturing process and techniques in terms of preventing leading edge erosion, by promoting the use of durable wood species [10], adding appropriate leading edge tapes [26] or using appropriate coatings [27]. In addition, the findings of the paper can guide practitioners and installers of LMSWTs on how to plan their preventative maintenance procedures in order to keep their small wind electric systems quiet and productive, and thus further increasing the sustainability of rural electrification applications.
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