Pages: 1-8 / Vol. 17- No. 1/Winter- Spring 2024

Journal of Aerospace Science and Technology

Journal Homepage: www:jast.ias.ir

Original Research Article

Experimental Investigation of the Effects of Leading-Edge Serration on the Blades of Savonius Wind Turbine

Sahel Alasvand, **Mostafa Kazemi**, **Mahmood Mani**[1]*

1-2-3- Department of Aerospace Engineering, AmirKabir University of Technology, Tehran, Iran

ABSTRACT

Due to the use of vertical wind turbines in electricity production, especially for domestic use, it is necessary to reduce annoying noise. The noise of wind turbines is mainly of aerodynamic origin and is caused by the impact of the flow on the turbine blade. Therefore, improving the behavior of the flow around the turbine and reducing aeronoise can result in reducing its annoying noise. One of the most widely used noise reduction methods is serration of the trailing edge or leading edge. Therefore, in the first step of this research, a suitable serration is selected according to the physics of the flow around the savonius. Then, it is installed on the leading edge of the blade in such a way that it does not cause the power loss of the turbine. All the studies have been done experimentally in the wind tunnel and with the help of power, pressure, and air velocity measurements in the wake and the free flow with different velocities. The results showed that the pressure fluctuations in the wind turbine equipped with a serrated blade have decreased by 4-9% on average in different areas compared to the simple Savonius. On the other hand, the results of the frequency analysis of the anemometer sensors also showed that in the dominant frequencies, the serration caused the range of phenomena to decrease. These results were obtained in such a way that the power measurement showed that the maximum power value of the turbine equipped with serrated blade experienced an increase of nearly 19%. On the other hand, the velocity profile in the wake also shows a greater deficit in the flow around the modified Savonius, which confirms the decrease in the output momentum from the turbine and, consequently, the increase in power.

Article History:
Received: 23.May.2023
Revised: 31.July.2023
Accepted: 07.August.2023

Keywords: *Savonius, Wind Turbine, Aeronoise, Experimental Aerodynamics, Wind Tunnel*

DOI
10.22034/jast.2023.398694.1150

Introduction

Much of the research conducted around the reduction of wind turbine noise are based on the preservation of human health and the acceptability of wind energy, and in order for the wind turbine to be in the vicinity of human habitations, problems such as noise reduction and structural vibration should be investigated. Studies show that the annoyance caused by wind tunnel noise is more than that of public vehicles [1]. Considering that the noise caused by the impact of the blade's leading edge with the flow is related to the atmospheric turbulent flow, changing the shape of the leading edge into a serrated shape is useful in reducing noise. According to the shape of the whale's fin, using the sinusoidal leading edge, and according to the owl's wing, using the serrated leading edge is effective, while it can have a penalty for the lift force [2]. By using the serration of the owl's wing, the flow around the airfoil can be modified, the boundary layer can be controlled, and the noise resulting from the pressure fluctuations of the airflow on the surface can be reduced [3], and because vertical turbines perform better at low velocities and in applications are also

1 (Corresponding Author) Mahmood Mani, Professor , **Email:** * mani@aut.ac.ir

Print ISSN:1735-2134 Online ISSN: 2345-3648

used domestically, they should be investigated and discussed in terms of noise pollution [4]. Noise generated by the turbulence boundary layer of the airfoil edge is one of the main sources of noise generation in wind turbines, which reduces power generation and increases the overall cost of energy generation. Among the important changes are the creation of serration, reduction of shear stress, and modification of the fluctuation spectrum, which leads to noise reduction [5]. savonius wind turbine is a vertical axis wind turbine based on drag force. Due to its simplicity and low noise pollution, it is a suitable option for use in urban environments.This wind turbine works at low velocities and does not require a mechanism for initial start-up [4]. Also, its performance does not depend on the direction of the wind and has a good performance in unstable winds [6].The aspect ratio is another factor influencing the performance of savonius. Numerical simulation and experimental tests show that the production power of a savonius turbine is directly proportional to its dimensions and aspect ratio. Increasing the aspect ratio from 0.5 to 1 significantly increases production power. Choosing the best aspect ratio is very important for power [7]. The noises created by the wind turbine are divided into two categories: mechanical and aerodynamic. Mechanical noises are created from moving components such as gearboxes, cooling fans, and generators. They are controlled by tools such as sound absorbers and nacelle protection. But aerodynamic noises are an important source of noise in turbines. The collision of the flow with the blade causes aerodynamic noises. Aerodynamic noises are divided into noise turbulence in-flow and airfoil self-noise. Turbulence noise is caused by the collision of turbulent flow with the blade's leading edge; this collision of turbulent vortices with the blade causes broadband noise, which is in the low-frequency range of up to 100 Hz and strongly depends on the turbulent flow. The second category of aerodynamic noises is divided into turbulent boundary layer noise and trailing edge noise. The trailing edge noise creates broadband noise with frequencies of 500-1500 Hz and is caused by the collision of the turbulent boundary layer with the trailing edge. At low Machs, this turbulent flow in the farfield or along an infinite plane is an ineffective noise source, but when it collides with a sharp edge, it strongly reflects and produces noise. Also, when the flow velocity is high, the noise caused by the trailing edge is an important factor [8]. The amplitude of the reflected noise is proportional to the fifth power of the blade Mach number, and the acoustic intensity is related to the flow's angle with the trailing edge. The flow around the vertical axis turbine blade has the possibility of stagnation at some points, so the pressure fluctuations may be dispersed and reflected [9]. The noise of the wing tip is caused by the tip vortices created due to the pressure difference between the upper and lower surfaces of the airfoil. These vortices cause broadband noise with very high frequency due to incidence at the tip and trailing edge. The noise of the blunted trailing edge, which has become the cause of noise due to van Karman vortices and depends on the Reynolds number and the change of the thickness of the boundary layer and the thickness of the trailing edge, and is eliminated with a trailing edge. The flow separated from the airfoil is also a noise factor, which is due to the increase of the angle of attack and the action of stalling, and as a result the flow is separated. The separated flow causes broad noise reflections and is highly unstable. Smooth separation causes trailing edge noise, while deep separating causes noise to be emitted from the entire chord and can be prevented by controlling the angle of attack. The laminar boundary layer is one of the factors creating noise, so its unstable part is associated with the vorticity of the trailing edge and creates noise. This noise can be prevented by cutting off the upstream boundary layer. Training edge noise is the main cause of noise in high frequencies, which can be reduced by the blunting model for high frequencies of 4000 Hz. Then, they tried the Ogi model, which was useful in reducing the noise and reducing the wet surface of the eddies. Also, the shark-like edge has a 7% reduction in noise, but it comes with a 3% reduction in power. Also, by attaching simulator vortices to solve the flow, the noise reduction reached 25% [10]. It is simply impossible to predict the noise the serration generates due to their different length and three-dimensional geometry. Therefore, several analytical and semi-analytical models were created to predict these noises. While predictions based on analytical models only require geometry details, semi-analytical ones require additional information on boundary layer characteristics and the spatial distribution of surface pressure fluctuations. The first analytical solution for a formulated serrated leading edge showed that in the time-averaged turbulent flow, for a smooth semi-infinite plate with a serrated edge, the noise reduction concerning the trailing edge is directly proportional to the length of the serration (h) and the wavelength (λ) depends. The geometric characteristics of the serration are generally shown in Figure 1. This model predicts noise reduction approximately by "Eq. (1)," [11]. Although this model is still widely used due to its simplicity, the predicted noise spectra in typical regions do not match the measurements. This formula predicts the maximum noise reduction, but it is useless for predicting noise at high frequencies.

$$10\log\left[1+\left(\frac{4h}{\lambda}\right)^2\right] dB \qquad (1)$$

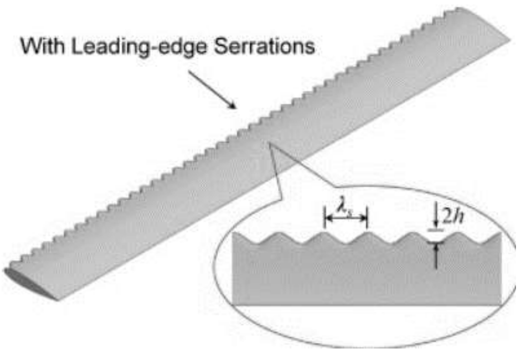

Figure 1- Geometric characteristics of the serration

In the obtained λ/h, due to the interference of the tip and root of the serration, there are strong fluctuations in the noise diagram, and in the larger λ/h, these fluctuations are much less and about 1 dB [12]. The reduction of noise increases by decreasing the ratio of wavelength to serration length [13]. When the airfoil is serrated at a low angle of attack, the vortex shedding frequency decreases, and the vortices disappear faster in the wake. If the serration is added to the length of the chord, the leading-edge vortex becomes larger, and the circulation also increases when the leading-edge vortex reaches the end of the serration, the stall occurs at a lower angle of attack and the leading-edge vortex starts rolling and is visible at a higher angle of attack, and the stall is delayed by about 1° and the vortices disappear faster [14]. It was found that using a serrated trailing edge is more effective in reducing noise than using a sinusoidal one. As the serration length increases, it gives us more noise reduction at low frequencies, and this noise reduction is less at higher frequencies [15]. In order to reduce the aerodynamic noise produced by a 10,000 W wind turbine, Lee [13] applied serrated trailing edges to the wind turbine blades. Two types of serrated plates and a rectangular plate were attached to the blades. Noise measurement was done according to IEC 61400-11 standard. Incoming freestream velocity, output power, and rotation speed of wind turbine were also recorded with the noise signal. A significant noise reduction of up to 5 dB was achieved, but it is expected that the noise reduction achieved is partly due to the reduction of trailing edge noise and partly due to the reduction of blunted edge noise. It was proved that noise reduction increases by decreasing the ratio of the wavelength to the serration amplitude. Matthew et al. [15] investigated that as the amplitude of the serration increases, there is a greater reduction in noise for low frequencies, and it increases at high frequencies. It is also observed that the 3D model performs better at low frequencies. The use of serration is a way to reduce the angle between the vortex path and the edge to less than 90 degrees because 90 degrees has the most noise. For a wind turbine with a diameter of 94 meters, noise reduction of 2.3 dB has been reported with the presence of serration, and the serration with variable input velocity cannot always be aligned with the flow direction. As a result, the serration led to an increase in noise at high frequencies. They use a comb and a hole, which reduces the noise of the airfoil [10]. Using different serration on the leading edge of a vertical axis wind turbine, Wang et al. [16] observed that the serration with a ratio of wavelength to height of 13.2 has the best performance, which is the highest performance factor at the blade tip speed equal to 2. According to previous research, methods have been proposed to reduce the noise of the wind turbine airfoil due to its deformation. It is worth mentioning that the use of serration is the most effective way to reduce the sound pressure level. The purpose of this research was to design and analyze a savonius wind turbine equipped with serration at the leading edge, considering the necessity of placing the vertical axis turbine in the vicinity of human habitations. The innovation of this research is the study of the effect of the serrated leading edge on the performance and noise of a savonius wind turbine. In this regard, a serration with a wavelength of 1 has been selected according to previous research and added to the leading edge of a simple savonius wind turbine. All these researches have been done experimentally in the wind tunnel using pressure sensors, hotwire anemometer and power measurement set at free-flow speeds of 5 to 10 m/s.

Experimental Methodology

In order to achieve the goals set in this research, the existing methods in experimental aerodynamics have been used, which will be mentioned in the following. In this research, a simple Savonius wind turbine was used as the main model of research, and then, by placing a serration, the effects of changing the geometry of the blade on the flow field around the turbine were investigated. The simple Savonius model consists of two semi-circles with a diameter of 16 cm, which, with a 1 cm overlap of the two blades, will produce a turbine with a rotor diameter of 30 cm. The turbine's height is selected as 23 cm according to the previous research, and also by using two circular plates with a diameter of 32 cm to eliminate the effects of three-dimensional blades in aerodynamic phenomena, the wind turbine related to this research was made. In addition to the simple model, a model equipped with serration on the leading edge, whose dimensions are selected based on previous research, is ready to be tested, and the use of the serrated model is actually the most important innovation of this research. In order to rotate the wind turbine in a balanced and symmetrical manner and also to eliminate the effects of unrepeatability of the experiments, the wind turbine is installed in a supporting structure and then placed in the wind tunnel. All the experiments have been done in the subsonic wind tunnel of Amir Kabir University of Technology. The test section has the dimensions of 1×1 m^2, which has the ability to increase the velocity up to 60 m/s. Using a honeycomb, three layers of mesh, and a nozzle density ratio of 9:1, this wind tunnel produces a maximum disturbance intensity of 0.1%. In order to adjust the speed of the incoming wind, a digital manometer manufactured by KIMO company and model MP200, with an accuracy of 0.1 m/s, was used. In order to measure pressure in the sequence of the model, a set of pressure sensors of Honeywell brand and model HSCDD005MDNN5 has been used with an accuracy of 0.25% of the maximum value of the sensor. The pressure sensors are connected to a 32-channel pressure rake with a length of 16 cm to measure the total pressure at different points. Also, in order to move the sensors, a three-directional traverse device with an accuracy of 1 mm has been used. In general, the area twice the diameter of the rotor in the direction of the blade's width and in the blade's wake has been covered so that the pressure has been measured in 16 locations and a total of 256 = 16 x 16 points in each free-flow speed. Also, in order to measure its speed and disturbances in the sequence, a hot wire ammeter has been used. Three hot wire probes have been used for measurement: one probe in the free flow, one probe at the edge of the blade, and one probe in the wake of the model to calculate and compare the disturbances of the turbine in different positions. The frequency response of the pressure sensor is 1 KHZ, and the frequency response of the hot wire is 20 KHZ. Figure 2 shows the schematic image of the wind tunnel and test equipment and their installation location. The experiments were performed in the form of free rotation of the turbine and at speeds of 5 to 10 m/s with a step of 0.5 m/s so that the rotation frequency corresponding to these speeds varied from 60 to 780 rpm.

The rotation measurement was done by connecting a laser tachometer to one side of the turbine shaft, and the power measurement was done by placing a DC motor on the other side. To measure power from variable resistance with values of 1.4, 2.4, 3.5, and 4.3 Ω for the basic model and values of 1.5, 2.3, 3.3, and 4.7 Ω for the serrated model in order to Maximum power extraction is selected. The amount of power and power coefficient is obtained according to Equation (2) and (3), in which P is power in watts, I is current in amperes, ρ is air density in kilograms per cubic meter, V is free flow velocity in meters per second, D is the diameter of the rotor in meters, R is the electrical resistance in ohms, and H is the height of the turbine in meters.

$$P = R \times I^2 \quad (2)$$

$$Cp = \frac{P}{(0.5 \times \rho \times V^3 \times D \times H)} \quad (3)$$

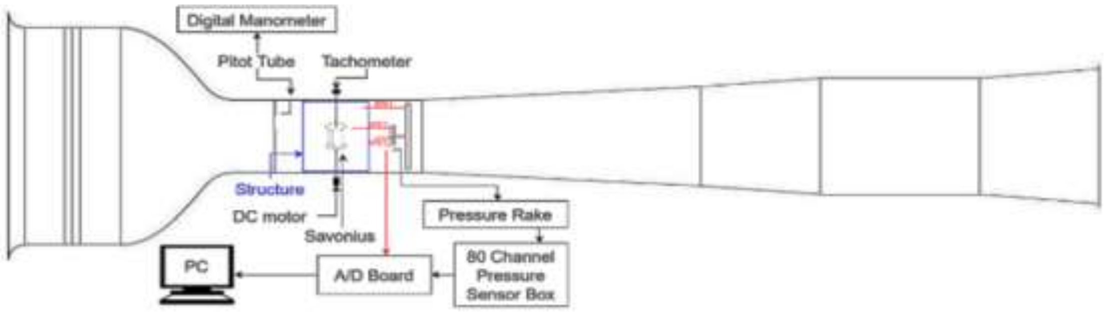

Figure 2- Schematic image of the wind tunnel

Results

According to the procedure explained in the previous sections, the results of the wind tunnel tests are included in this section. The process of analyzing the results is that at first, with the help of the constructed set, the power coefficient of the simple and serrated Savonius turbine has been obtained. Figure 3 is the graph of changes in power coefficient related to the simple model in different resistances. As it is known, the maximum power factor for this turbine occurred at a tip speed ratio of 1.16, which is constant in almost all resistances, which actually indicates the point where the turbine's production power drops compared to the momentum of the input flow, in fact, the energy The inlet fluid increases the turbine rotation velocity and does not produce power because the rotation velocity has increased significantly. The maximum power coefficient that Savonius turbine reached was more than 0.08. Also, the results show that the behavior of different consumers on the performance of the wind turbine was in such a way that the slope of the increase in the power coefficient changed with the increase in the speed of the incoming flow. Still, the increasing trend and the maximum point were without difference. Figure 4 shows the performance coefficient of the serrated model in terms of the blade tip speed ratio, the maximum of which occurred almost the same as the turbine without serration. Then due to the growth of the boundary layer and the high velocity of the turbine rotation, the flow did not have the opportunity to enter the turbine and the power was drops significantly. The presence of turbulence intensity increases the amount of kinetic energy to be harvested but reduces the efficiency of the turbine after a certain speed. The results of conducting tests on different resistances to extract the consumer's effects on the wind turbine's performance showed that the resistance of 4.7 Ω had the highest efficiency. In order to study the impact of the serration on the performance of the Savonius model, it can be seen in Figure 5 that the serrated wind turbine has increased the performance by more than 19% compared to the base turbine in the maximum value. It can also be seen that the impact of the serration is not the same on the turbine's performance, and it shows a different impact in the ratio of different tip speeds. The physical cause of this issue can be caused by the change in the way vortices are produced in the turbine with the presence of serration. In Figure 6, the changes of air velocity in the wake of the model extracted from the pressure rake at a longitudinal position of 45 cm compared to the trailing edge of the turbine corresponding to the two basic and serrated models are drawn at the free flow velocity of 9.5 m/s. As it is known, the amount of graeter deficit in the wake of the serrated model is more, which shows the decrease in the output momentum of the turbine compared to its input, which represents the drag force created in the turbine. This issue shows that the production power of the serrated turbine is higher than the basic model, which confirms the results of the power coefficients.

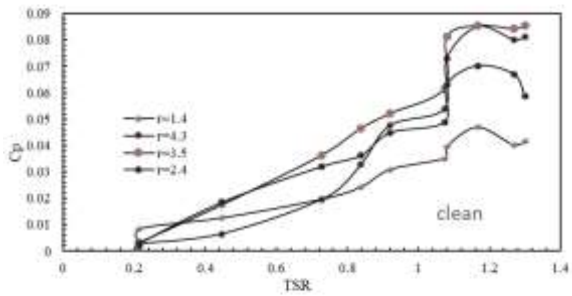

Figure 3- Performance factor of the basic model according to blade tip speed ratio

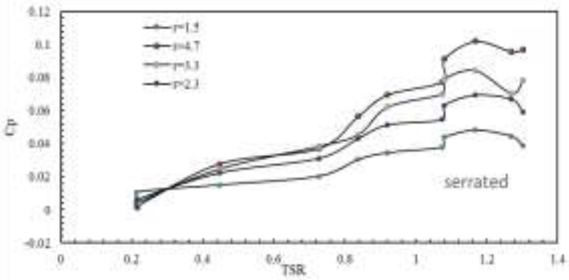

Figure 4- Performance factor of serrated model according to blade tip speed ratio

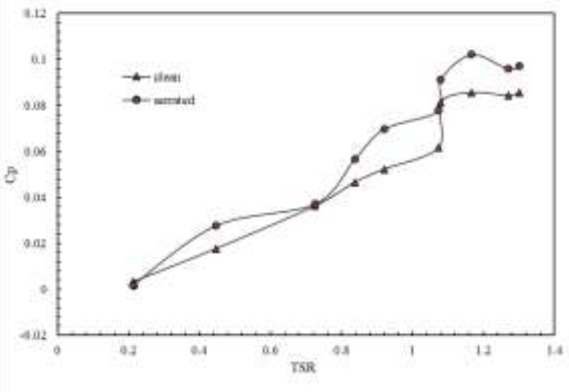

Figure 5- Comparison of performance coefficient of two models according to blade tip speed ratio

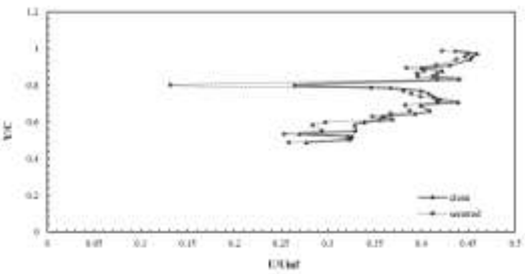

Figure 6- Comparison of the velocity profile in the wake of two models

The results of the experimental investigation showed that the use of serration for Savonius wind turbine can significantly increase the power and does not have a detrimental effect on its performance. Now, the effects of the serration on the aerodynamic noises around the turbine are investigated. As explained in the previous section, in order to study the effects of serration on the acoustic field around the wind turbine, a series of pressure and velocity measurement experiments have been prepared, the results of which will be discussed later. Pressure fluctuations at a velocity of 7.5 m/s for two base and serrated models at a relative distance of 30 cm from the trailing edge are shown in Figure 7. As is evident from the figure, the pressure fluctuations in the middle of the turbine are where the biggest drop in velocity actually occurs. In fact, due to the local speed increase on one side of the turbine, the pressure fluctuations are reduced due to the higher momentum of the flow. Notably, in the middle areas and near the trailing edge of the blades, a reduction in pressure fluctuations is observed in the model equipped with serration. In fact, in some regions, pressure fluctuations have been reduced by 10%, equivalent to 1 pascal, which can significantly affect noise reduction. The reason for this can be the modification of the flow pattern and the drop of vortices due to the presence of the serration and the increase in the turbulence of the input flow to the turbine. Figure 8 shows the changes in pressure fluctuation related to base and serrated models at a relative distance of 30 cm from the trailing edge at a velocity of 9.5 m/s. As it is known, the amount of pressure fluctuations is higher in the direction of the center of the turbine, and the velocity deficit region and the lowest pressure fluctuation are related to the place where the local velocity increase is caused by the rotation of the turbine. In order to more accurately investigate the flow around the savonius wind turbine and also the effects of adding serration to the leading edge of the turbine on the amount of noise it produces, after investigating the pressure fluctuations over time, the velocity fluctuations in the frequency domain will be investigated. All results related to the frequency analysis of the hotwire sensor in the sequence of both different models at two speeds of 7.5 and 9.5 m/s are presented in Figures 9 and 10. The frequency analysis results show that the amplitude of the flow fluctuations in the dominant frequencies of the chart has been reduced with the help of the serration on the leading edge of the turbine. In fact, any dominant frequency in the frequency analysis chart can represent a vortex shedding or a flow phenomenon that has resulted in its reduction due to the presence of the serration in all frequencies. It can also be seen that at high frequencies, in the serrated model, the frequency of phenomena has increased. This issue is deduced that broken or smaller vortices are formed due to the presence of the serration, which have higher frequencies.

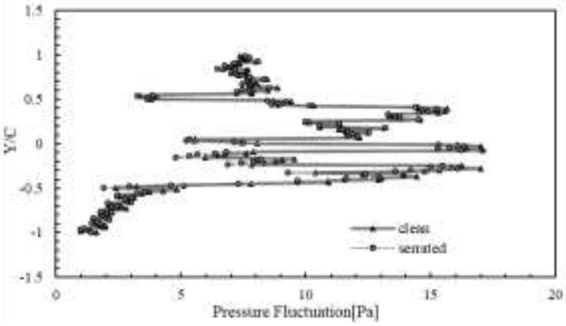

Figure 7- Comparison of pressure fluctuations of two models at the velocity of 7.5 m/s

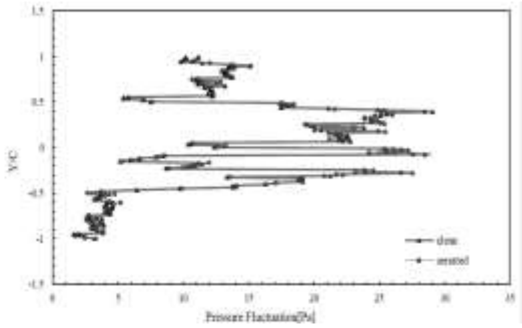

Figure 8- Comparison of pressure fluctuations of two models at the velocity of 9.5 m/s

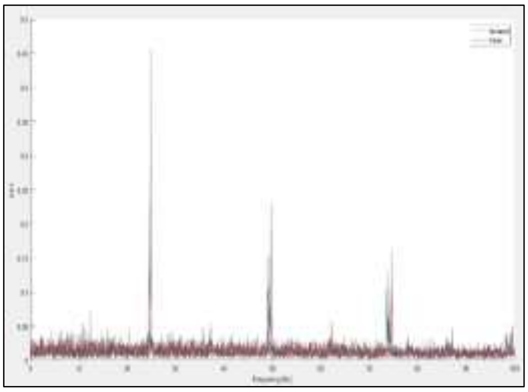

Figure 9- Comparison of frequency analysis of two models at the velocity of 9.5 m/s

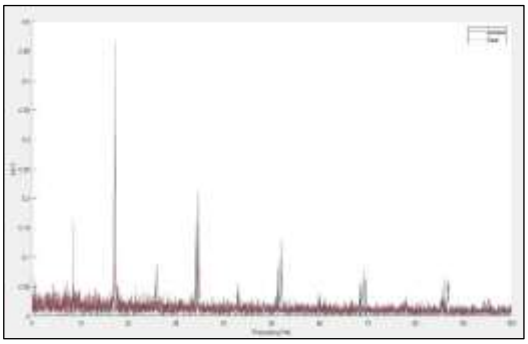

Figure 10- Comparison of frequency analysis of two models at the velocity of 7.5 m/s

Conclusion

The main focus of this paper is to investigate the effect of serration on the leading edge of a simple Savonius wind turbine on aeronoise. The turbulent impact of the flow on the leading edge of the blade causes broadband noise. By designing a serration with a ratio of wavelength to the amplitude of 1, a way was found to reduce the angle between the vortex path and the leading edge to less than 90 degrees, which makes the noise less scattered and does not bring the power loss. The presence of the intensity of turbulence increases the amount of kinetic energy for harvest but reduces the efficiency of the turbine after a certain velocity. In the graphs related to the power, it was observed that both models have a power loss at a certain velocity, but on average, the power of the serrated model is greater, which can be the reason. The velocity deficit in the serrated wake is more than the base turbine, which can also justify the performance of the power diagram. The pressure fluctuations, which are considered noise in the far field, are less in the serrated model. The amount of induced rotation energy has decreased and reduced the frequency of vortex shedding. As a result, adding a serration with a ratio of wavelength to amplitude of 1 to the leading edge of the Savonius airfoil in the continuation of its chord reduces the pressure fluctuations in the far field and gives a greater velocity deficit, which confirms the increase of power. Also, the frequency effect of the serration was visible in the dominant frequencies, which reduced the frequency range of the corresponding phenomenon.

Conflicts of Interest

The authors of this paper declared no conflict of interest regarding the authorship or publication of this article.

References

[1] E. Pedersen, K. Persson Waye, "Perception and annoyance due to wind turbine noise—a dose–response relationship, " The Journal of the Acoustical Society of America., 116(6): p. 3460-3470,2004.

[2] F. Avallone, et al.,"Noise reduction mechanisms of sawtooth and combed-sawtooth trailing-edge serrations, " Journal of Fluid Mechanics., 848: p. 560-591, 2018.

[3] C.H.T. and J.L. Liu. "Bionic Design Review of Wind Turbine Blades, " in Advanced Materials Research., Trans Tech Publ,2012.

[4] F. Wenehenubun, A. Saputra and H. Sutanto, " An experimental study on the performance of Savonius wind

turbines related with the number of blades, " Energy procedia.,68: p. 297-304, 2015.

[5] C. León, et al., " Boundary layer characterization and acoustic measurements of flow-aligned trailing edge serrations, " Experiments in fluids., 57(12): p. 1-22, 2016.

[6] L. Chen, J. Chen and Z. Zhang, "Review of the Savonius rotor's blade profile and its performance, " Journal of Renewable and Sustainable Energy., 10(1): p. 013306 ,2018.

[7] A. Zakaria and M. Ibrahim. "Effect of twist angle on starting capability of a Savonius rotor–CFD analysis, " in IOP Conference Series: Materials Science and Engineering, IOP Publishing., 2020.

[8] S. Wagner, R. Bareiß and G. Guidati, "Noise Mechanisms of Wind Turbines, " in Wind Turbine Noise Springer., p. 67-92 ,1996.

[9] C. Pearson," Vertical axis wind turbine acoustics.", University of Cambridge.,2014.

[10] S. Oerlemans, " Wind turbine noise: primary noise sources. ", 2011.

[11] M. Howe, "Aerodynamic noise of a serrated trailing edge. " Journal of Fluids and Structures., 5(1): p. 33-45,1991.

[12] P. Chaitanya, et al., " Performance and mechanism of sinusoidal leading-edge serrations for the reduction of turbulence–aerofoil interaction noise. " Journal of Fluid Mechanics., 818: p. 435-464,2017.

[13] S. Lee. "Wind turbine noise reduction by means of serrated trailing edges. " In INTER-NOISE and NOISE-CON Congress and Conference Proceedings. Institute of Noise Control Engineering.,2012.

[14] K. Gharali,N. Tam and D.A. Johnson. "A PIV load and flow structure study of a serrated dynamic airfoil. " in Lisbon 17th Int. Symp. On Applications of Laser Techniques to Fluid Mechanics., Lisbon, Portugal. 2014.

[15] J. Mathew, et al. " Serration design methodology for wind turbine noise reduction. " In Journal of Physics: Conference Series. IOP Publishing,2016.

[16] Z. Wang and M. Zhuang, " Leading-edge serrations for performance improvement on a vertical-axis wind turbine at low tip-speed-ratios. " Applied Energy, 208: p. 1184-1197,2017

HOW TO CITE THIS ARTICLE:

Sahel Alasvand, Mostafa Kazemi, Mahmood Mani, "*Experimental Investigation of the Effects of Leading-Edge Serration on the Blades of Savonius Wind Turbine*", Journal of Aerospace Science and Technology,Vol 17- No1, 2024, pp, 1-8

DOI: doi.org/10.22034/jast.2023.398694.1150

URL: https://jast.ias.ir/article_176856.html