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Computational and Experimental Investigation of Lotus-inspired Horizontal-Axis Wind Turbine Blade

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ABSTRACT

In the firm belief that the world needs green, renewable and more efficient energy resources, the present paper is concerned with developing a new design for horizontal-axis wind-turbine (HAWT) blades. The flower of Nelumbo nucifera (Sacred Lotus) was the motive for the present design of a three-blade wind turbine. Nelumbo Nucifera flower has an aerodynamically appropriate structure, which qualifies the flower to be the nature-inspiration for the present research. A computational fluid dynamics (CFD) simulation was applied in order to ensure the ability and eligibility of the proposed solution and estimate real world's results. The performance of the blade airfoil can be improved by applying the Lotus flower's structural design and modifying the blade straightening. The experimental findings demonstrated performance enhancement by 31.7% compared to NACA 2412 airfoil.

1. Introduction
1.1 Background

Green energy is becoming the main interest to all scientists. For many decades, renewable energy is estimated to be the main source of energy. However, renewable energy does not provide commercial efficiency compared with steam turbines. Renewable energy is exposed to continuous developing, the global demand of energy for the next decades is predicted to be relying on renewable energy. So, all the studies of wind energy tend to increase the efficiency of the turbines and improve their farm size, or changing the blade design to make it more efficient. There are many sources and methods that scientist can use to improve this design. One of these sources is Bio-inspiration.

Bio-inspiration is a proficient discipline of engineering based on taking an idea from the environment and making benefit from it in a different way to become more productive. The growing demand for energy security and sustainable development dictated a need for renewable energy

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resources. Renewable energy became an essential part of the energy production industry as it contributes with about 14% of the total energy supply in 2015 and expected to increase to about 63% by 2050 [1]. Renewable energies are zero-emission energies that make them eco-friendly and contribute in the decrease of CO_2 production.

Wind energy is one of the fastest rising segments of renewable energy and is considered the second most important type of renewable energy after hydropower [2]. Wind energy is produced using turbines, offshore and onshore, which usually produce some noise but by improvements in the design, the noise level has noticeably dropped [3]. Betz's law estimates, from the conservation analysis of mass and momentum in the fluid flow through the turbine, the highest efficiency that can be obtained from a wind turbine is by decreasing the speed of air by 59.3%.

This research concerns a new design for horizontal-axis wind turbines (HAWT), which was inspired from Louts flower as its anatomy guarantee reduction in the speed of airflow. Thanks to the aerodynamic structure, the blades of the turbine reduce the speed of airflow, which assures higher revolutions per minute (RPM) and enhanced output by association.

1.2 Previous Investigations

(A) Structural Design and Manufacturing Process of a Small-Scale Bio-Inspired Wind Turbine Blade

A study from Pontifical Bolivarian University led by the author Herreraa *et al.,* [4] was focused on establishing blade shape that is inspired from the geometry of "Triplaris Americana seed". The design simulates the rotation mechanism of the seed during falling commonly in flora of Colombia. The research performed two different studies: first study to determine the seed 's free fall speed and its corresponding angular speed; second study featured the seed 's airfoil and curvature qualifying. After testing the first study showed free fall speed of 1.5 m/s in addition to angular speed of 1500 RPM. The second study resulted in average airfoil shown in Figure 1. Different wind speed was used during stimulation the curvature of the airofoil, the speed ranged from 7 m/s to 25 m/s with average error of 4.4%.

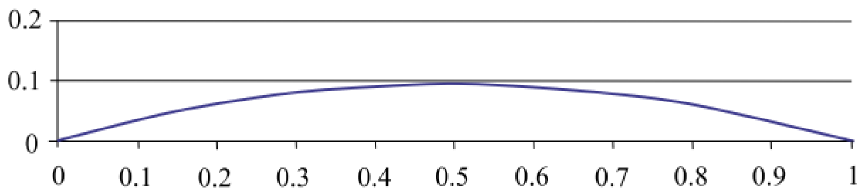

Fig. 1. Speed airfoil average

A 3D model was utilized to detect the torque the blade was 3.8 meters using wind speed of 12.5m/s, the output was power of 5.1kW in addition to the power coefficient (Cp) which was calculated in conditions of speed ranged from 3 m/s to 13 m/s and blade diameter ranged from 1m to 5m as shown in Figure 2 and Figure 3.

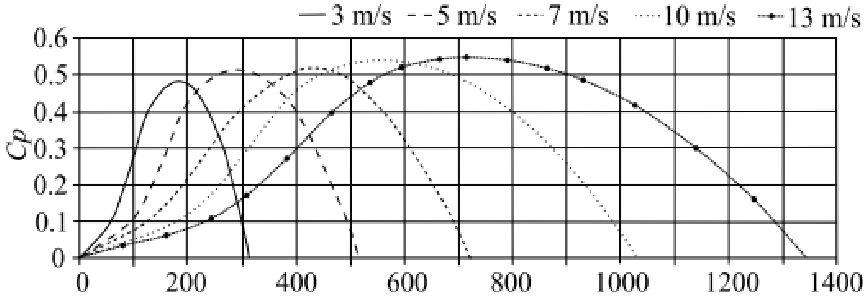

Fig. 2. Cp performance at various wind conditions

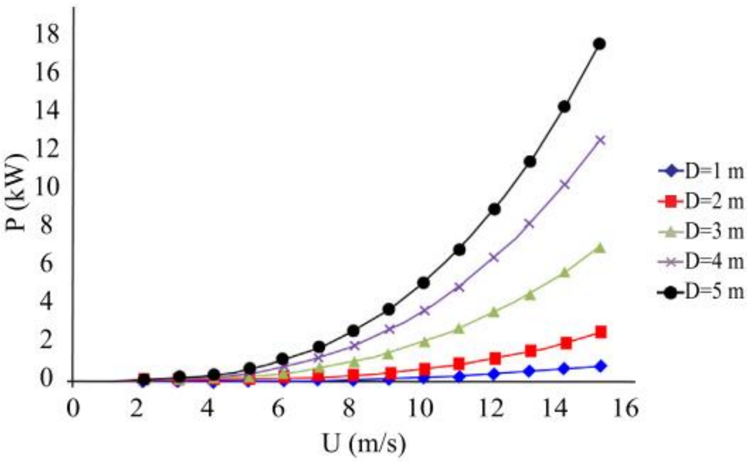

Fig. 3. Power performance

A 3d model shown in Figure 4 was created in order to use in the Aerodynamic simulation for a horizontal- axis wind turbine (HAWT) with the modified design of the blade. It was tested in similar conditions to the real conditions in the wind farms. The model was simulated at a wind speed of 13 m/s with an air density of 1.225 kg/m^3 and a pressure of 101325 Pa. taking into account the pressure distribution along the blades and aerodynamic forces.


Fig. 4. 3D-model of "Triplaris Americana seed" HAWT

The aerodynamic design of the turbine came up with a practical geometry with a validated aerodynamic structure with an error factor of 8%. A hardware prototype of the wind turbine made of composite carbon fiber was manufactured in order to characterize the power conversion efficiency. A minimum wind speed of 2.5 m/s was required to start producing energy and the peak of the power coefficient was 0.55 under real conditions as shown in Figure 5. The model had external parameters that can affect the performance like moisture and fatigue response, which can be considered as weaknesses of the model.

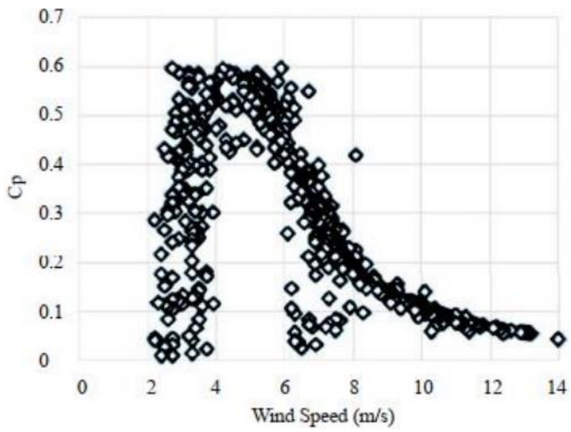

Fig. 5. Triplaris Americana seed" model performance

(B) "Dryobalanops Aromatic seed"- inspired HAWT blade

A research was conducted by Chu and Chong [5], that was concerned the study of the performance of bio-inspired horizontal-axis wind turbine inspired by "Dryobalanops aromatic seed" as shown in Figure 6. To generate the 3-D design of the blade, different photos of the seed were taken in various perspective angels. Then, the design mimics the edges and midsection of the wing sections extracted from the photos using GetData Graph Digitizer. Finally, the geometric model had a scale of 0.9m in aspects of diameter.

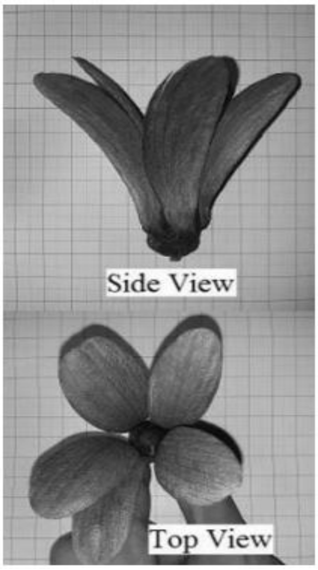

Fig. 6. Dryobalanops aromatic seed" model

The model that was created had fair maximum power coefficient compared to typical HAWTs. The "Dryobalanops aromatic seed" seed had five elastic wings and its shape was similar to a shuttlecock in addition, it gives the model some of the seed ability to align itself against wind flow. The final proposed horizontal axis wind turbine (HAWT) contains three flexible blades as shown in Figure 7. This design allows the model to have the ability in coning and passive yawing mechanism during its operation.

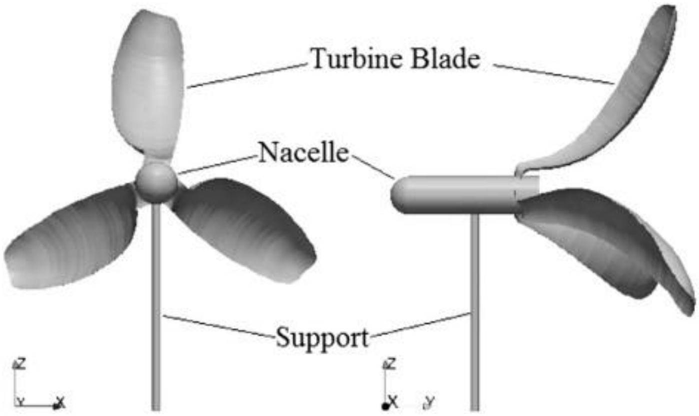

Fig. 7. 3D model of Dryobalanops aromatic seed" HAWT

The volume of the materials used in constructing the blade was the same used in experiment conducted by Krogstad and Lund [6]. The biomimetic wind-turbine blade orientation was adjusted to produce the highest possible power coefficient, Cp, at 10 m/s. The pitch and the cone angle, which was 42°, were the two standards involved in the biomimetic blade enhancement. The results of the CFD simulation showed that the maximum Cp of the "Dryobalanops aromatic"-inspired wind turbine was 0.386 at TSR = 1.5, which is 16.75% lower than the maximum Cp of classical wind turbines, which guarantees better efficiency and profitability in the markets. The induced torque for the proposed biomimetic wind turbine at starting phase, when TSR was 0, was 2 N.m, which was 772% higher than classical wind turbines, which leaded to predicting that the "Dryobalanops aromatic"-inspired wind turbine could outperform classical wind turbines in the aspect of self- starting and performance in lower wind-speed conditions [6]. The centrifugal force on the blade was predicted to be excessively high. The model was cost efficient, produced high torque and was able to operate in low wind-speed conditions.

(C) A Robust Biomimetic Blade Design for Micro-Wind-Turbines

The research was conducted in Chiba University and focused on applying the aerodynamics of birds' wings to fabricate a new flexed-blade design for horizontal-axis wind turbines (HAWT) [7]. Such design would improve the robustness of small wind-turbine blades as birds' wings are comparatively in the same size-range of small wing turbines. The biomimetic blade was able to achieve high integral power coefficient over a wide array of tip-speed ratios (TSR) by combining computational fluid dynamic modelling, blade optimization, and wind tunnel measurements. For example, Miklosovic *et al.,* [8] reported that tubercles on the leading edge of a humpback whale flipper delay stall at large angles of attack, resulting in high lift. The utilization of leading-edge tubercles as blades could increase wind turbine power output [9].

Bio-inspired blade from birds wings usually has a flex with some swept-back angel in addition, to the flexed model of the blade which based on the aerodynamic characteristics with computational fluid dynamic (CFD) simulations.

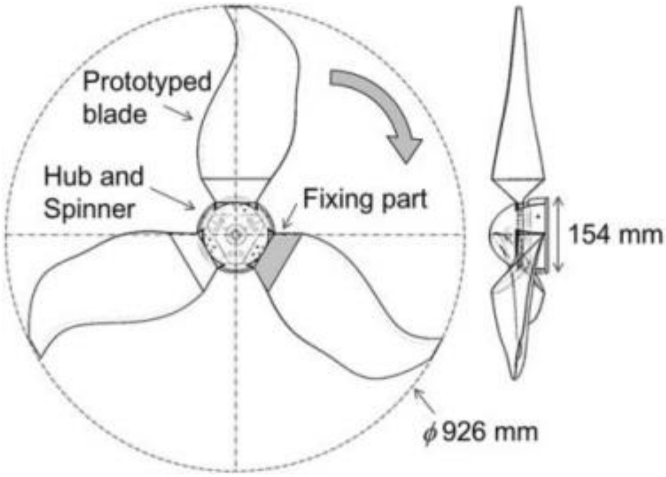

Fig. 8. Biomimetic blade design for micro-wind-turbine

The basic blade model was attached to a three-bladed turbine shown in Figure 9, connected to AC circuits. The HAWT model was based on the commercial Ampair 100 small wind-turbine with a 4-rotor diameter of 926 mm, a hub diameter of 228 mm, and a cross-sectional MEL012 airfoil.

The results also showed that bio-inspired bird blade with the optimized flexion has a higher aerodynamic performance in an aspect of power coefficients.

The results demonstrated that the swept-forward design to wing root increased Cp at smaller λ (TSR) as shown in Figure 10. In the inner-flexion blade, it is seen that at larger flexion angles ($x^2 > 0.08$ m), a higher Cp was generated at the smaller of 0.926 compared with that of the rectangular blade.

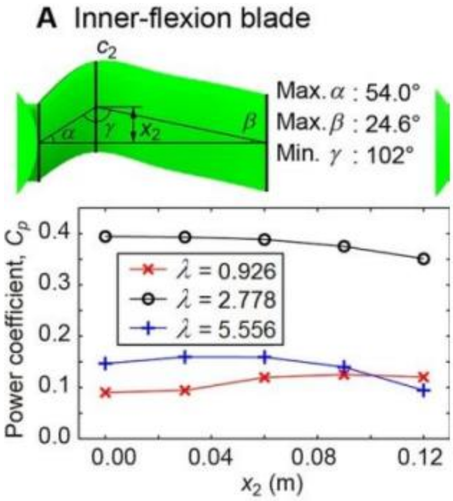

Fig. 9. Power coefficient (Cp) performance for the micro-wind-turbine

The simulation was performed for static loading to show a correlation between the blade geometry and orientation in order to determine the loading patterns of each blade. There was a significant increase in Cp as the velocity increased. However, the study was not loaded cyclically. Thus, future considerations to fatigue and failure experimental validation had not yet been completed. Finally, the new bio-inspired optimized-flexion blade had achieved the best robustness in power output by boosting the conventional BEMT blade by 8.1. Also, the bio-inspired optimized-flexion blade design has greater potential with typical wind turbines in addition, this design can increase the innovation of more complex design of wind turbine which mimic the environment and increase the efficiency.

(D) “Maple seed”-inspired Small Wind-Turbine Blades [10]

By studying the lift generation of Maple and Triplaris Samara seeds was conducted in addition to studying the structural analysis of the whale tubercles in an attempt to improve the efficiency of VAWTs. The main software used for the simulations was ABAQUSCAE. The seed converts the potential energy into kinetic energy in falling and into lift to keep aloft. The aerodynamically structure inspired researchers to simulate VAWT blade inspired by the seed. It was noticed that at 10 m/s wind speed, the maple seed blades deflected downward. This was attributed to the fact that the lifting force generated by the airflow was not strong enough to resist the gravitational force generated by the mass of the maple seed blade. It was shown that the wind turbine blades of the maple seed wind turbine could endure strong wind speeds of up to 55 m/s, which made it better than classical turbines. It was observed that there was a relation between the increasing rate of wind speed and the pressure load, as shown in Table 1.

The simulation was performed for static loading to show a correlation between the blade geometry and orientation in order to determine the loading patterns of each blade. There was a significant increase in Cp as the velocity increased. However, the study was not loaded cyclically. Thus, future considerations to fatigue and failure experimental validation had not yet been completed.

Fig. 10. Left: Maple seed, right: Triplaris Samara seed

Table 1
Relation between airflow speed and pressure load

Wind speed (m/s)	Pressure load (Pa)
10	31
15	69
20	123
25	192
30	276
35	376
40	490
45	621
50	766
55	927

1.3 Present "Lotus" Selection

Floating on the Nile, Lotus is considered one of the abundant flowers in Egypt that is not only used for decoration, but it also represents the old Egyptian culture and hides many parts of history between its leaves. In Egypt, lotus is uncommon in southern Egypt, but it can be found on the riversides in Northern Egypt [11,12]. Lotus is also considered as a vital ecological resource that helps in the decontamination of water from heavy metals [13]. Lotus importance is not limited by its ecological or historical importance, it has an important medical role as it was used as a cure for liver diseases in addition to its usage as an antiepileptic against jaundice and as a cooling herb. Its roots and their syrup were also used as a cough sedative, anti-diarrhoea, and as an anti-inflammatory [14].

According to Betz's law, the highest efficiency we can get from a wind turbine is by decreasing the speed of air by 59.3%. By examining the structure of the Nelumbo Nucifera petals, it was found that the design of its petal meets the needed requirements to apply Betz's principles.

Fig. 11. Side view of Nelumbo Nucifera Petals

2. Present Investigation

2.1 Computational Study

The computational study was carried out by the scientific software ANSYS 2021 R1 [15]. The study was concentrated on the turbine blade.

2.1.1 Geometry of the blade of the turbine

The lotus-inspired blade used for the computational calculations is demonstrated in Figure 12, the model was generated with the following dimensions

- Length: 1500 mm
- Width: 334 mm
- Binding angle of 20° between the tip and the middle of the blade, and a curvature of 60° between the leading edge and the trailing edge.

Actually, for real life use, wide range utilization the blade length is about 60 m, and for domestic use and home wind turbines the blade length is about 0.5 m.

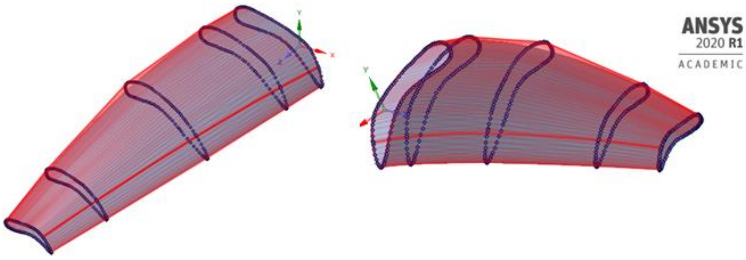

Fig. 12. Geometry views of a Lotus-inspired blade from different perspectives

2.1.2 Meshing

The mesh of the 2-D airfoil was generated using ANSYS Meshing 2021 R1. The average element size is 5 mm with a maximum skewness of 0.8, the mesh generated is illustrated in Figure 13. Tetrahedral unstructured meshing was utilized in order to generate a 3-D mesh for the blade, 47,8021 elements were generated with a maximum skewness of 0.844. The average element size was 325 mm. Figure 14 represents the final mesh for the 3-D blade and Figure 15 illustrates an outer perspective of the domain.

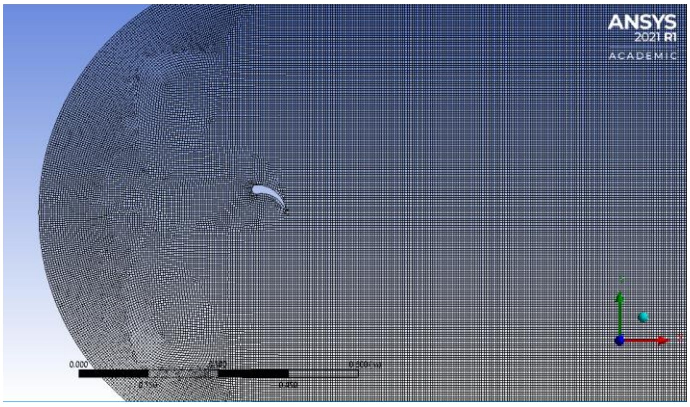

Fig. 13. 2-D mesh for the lotus-inspired airfoil

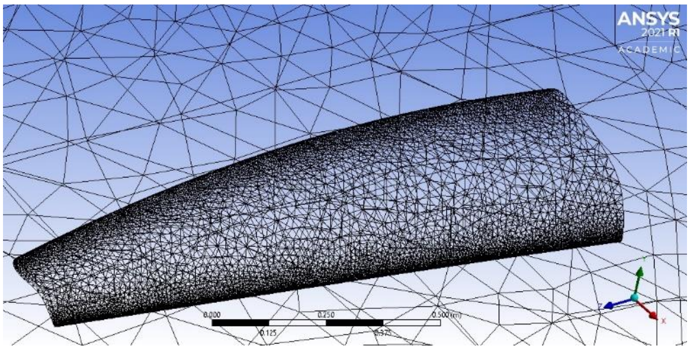

Fig. 14. 3-D computational mesh generated for the Blade

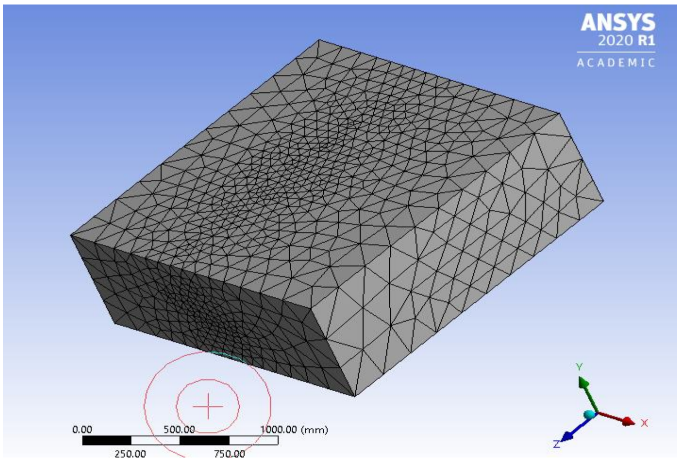

Fig. 15. 3-D computational mesh for the domain

2.1.3 Boundary conditions

The boundary conditions around the turbine blade were similar to the actual conditions for a horizontal-axis wind turbine. Inlet wind speed was 12 m/s with turbulence intensity of 5%. Outlet pressure gradient of zero. The distance between the inlet and outlet boundaries was 18 cm. Solid wall boundary condition was applied for the blade surfaces.

2.2 Experimental Models

Two small 3D-HAWT models of the standard NACA 2412 and N.Lotus-inspired blades were fabricated by a 3D-printer. The material used to manufacture the 3D printed models was PLA Filament 1.75 mm. The machine used in printing was UltiMaker 2+ extended [16] with a layer height of 0.15 mm. Each blade of both the two models was 60 mm in length. Both models were connected to 9 Volts-DC generators. Figure 16 illustrates the final models that were tested in the experiment.

Fig. 16. The two present 3D-printed models; Right: NACA 2412 model, Left: N.Lotus model

2.3 Generator

As there was no availability of finding a suitable generator, a 9 Volts-DC motor was used to produce electricity from the turbines. The utilized generator guaranteed high speed reach of 1600/3200 RPM. Generators with high RPM assure high capacity of electricity from the turbine. As the body of the generator has a wide base of about 33 mm and length of 25 mm, these features ensure high accuracy in obtaining results.

3. Results and Discussion

3.1 Computational Results

The computational results are promising as Lotus-inspired turbine blade demonstrates high efficiency in real-life conditions. The computational results show the apparent progress in the values of both pressure and speed of airflow around airfoil of the blade.

In order to generate the CFD results of the 2-D airfoil, seventy iterations were done by Ansys Fluent 2021 R1 as shown in Figure 17.

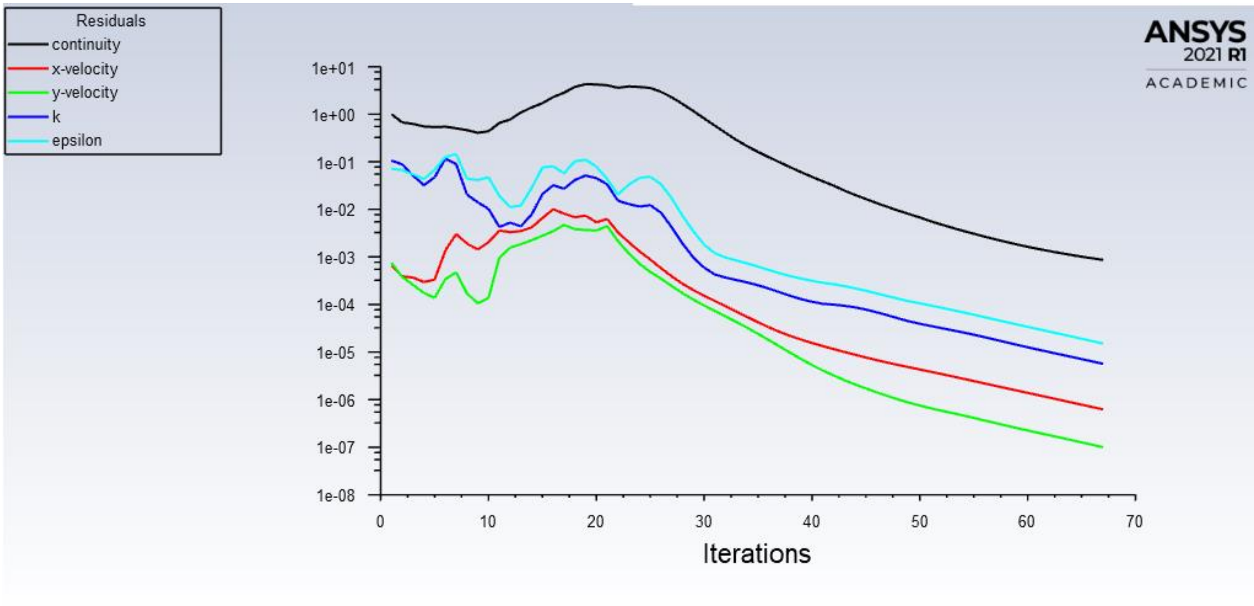

Fig. 17. iterations of the 2-D solution

Figure 18 shows the velocity contours around the Lotus-inspired blade section (airfoil). The present airfoil was compared to NACA 2412 Airfoil illustrated in Figure 19, the comparison shows that the lotus-inspired airfoil is capable of obstructing the airflow that passes through the domain of the blade and preserving the aerodynamics of an airfoil at once [17,18]. Figure 20 represents the contours of pressure on the blade airfoil.

Two hundred iterations were done in order to generate the results for the 3-D Lotus-inspired blade, the iterations continued to be computed till it became stable so that the most suitable results can be created. Figure 21 shows the iterations graph.

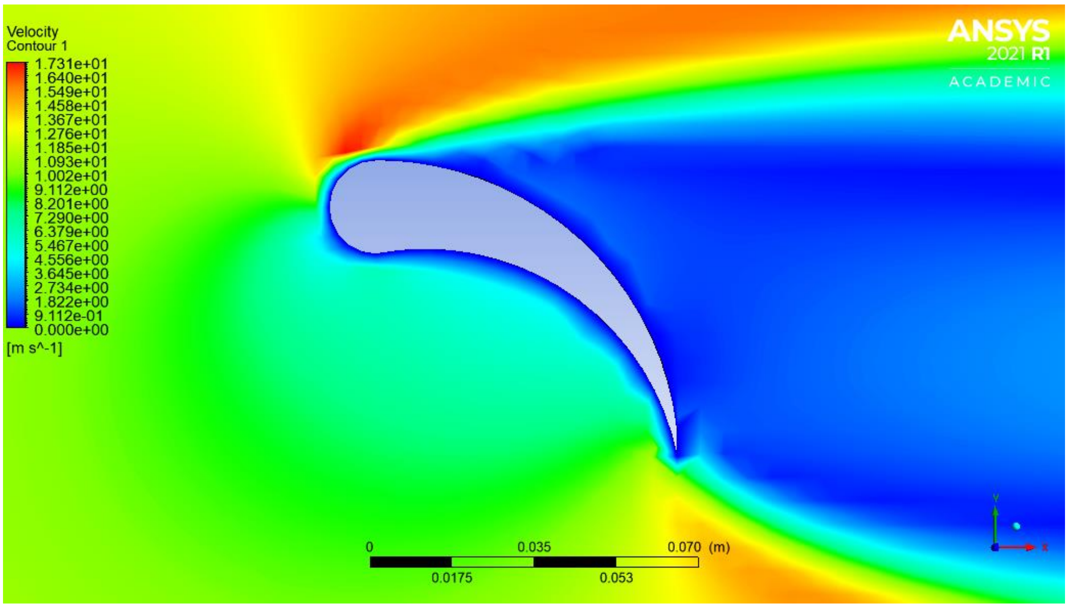

Fig. 18. Velocity contours around the Lotus-inspired blade section (airfoil)

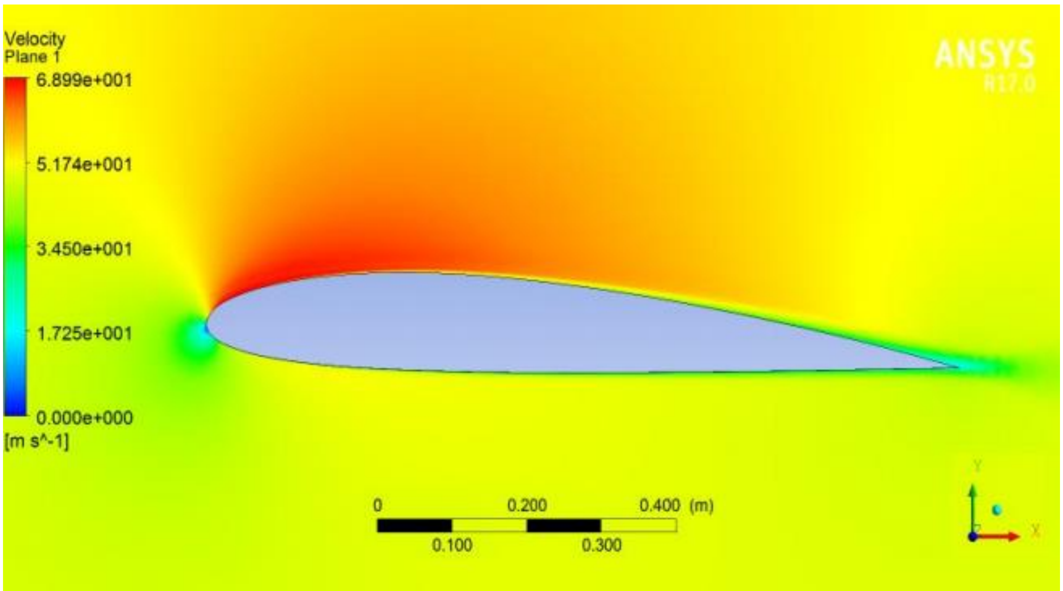

Fig. 19. Velocity contours around NACA 2412 Airfoil

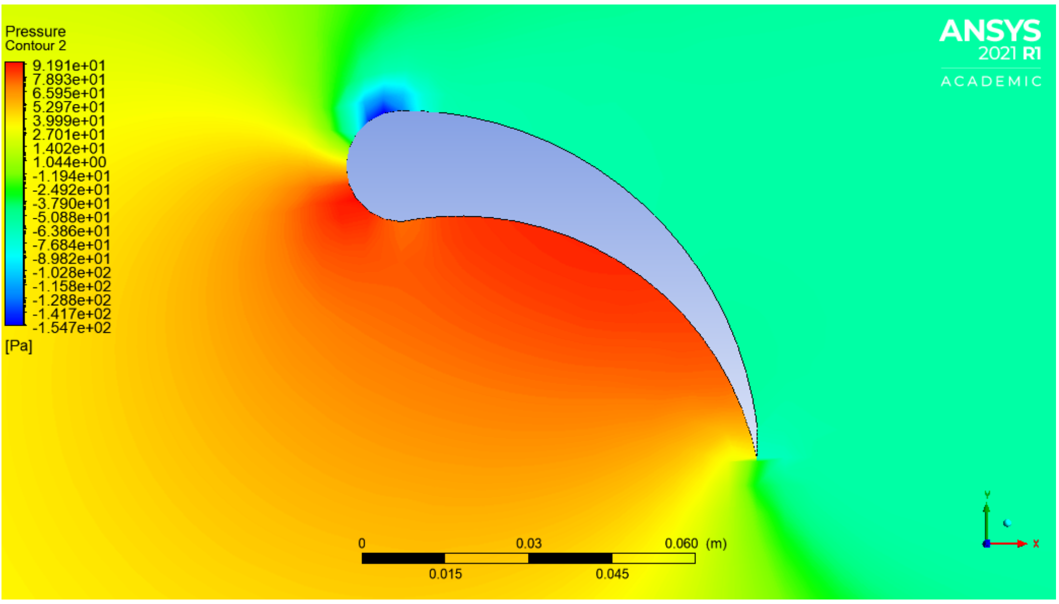

Fig. 20. Pressure contours around the Lotus-inspired airfoil

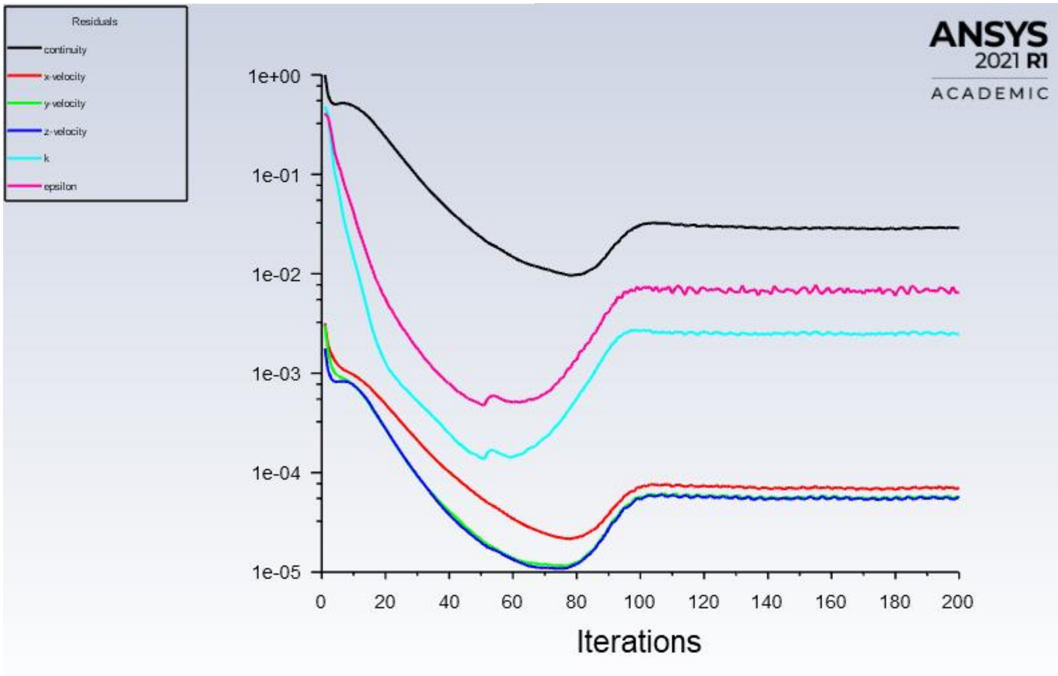

Fig. 21. iterations of the 3-D solution

The CFD simulation for the airflow around the whole blade was conducted, the results proved that the modified airfoil and structure are valid. As shown in Figure 22, the velocity streamlines are illustrated as vectors of 12 m/s with a maximum velocity of 30 m/s at the top of the blade.

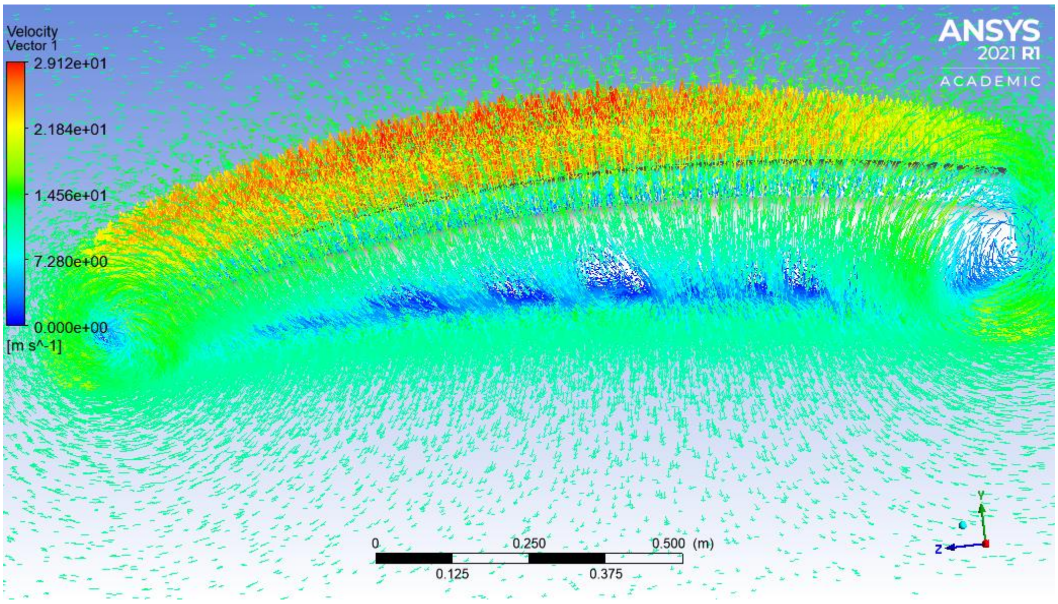

Fig. 22. Velocity streamlines around the blade

The contours of static pressure on the blade were generated and presented in Figure 23. It is concluded that the results are reasonable and acceptable.

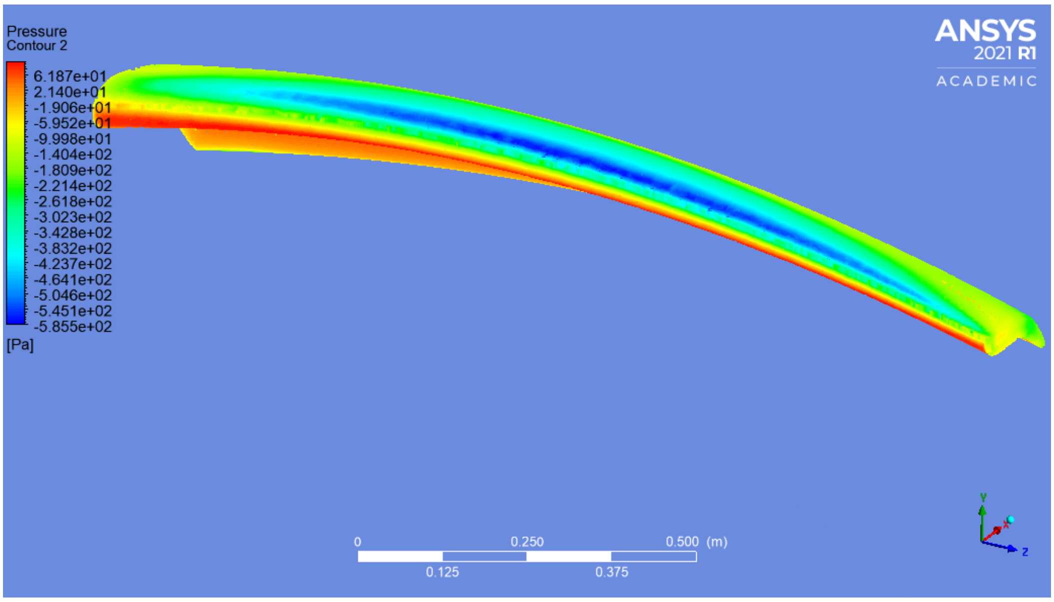

Fig. 23. Contours of the static pressure on the Lotus-inspired blade

The present equation represents Reynolds number law for the blade

$$\mathrm{Re} = \frac{\rho \upsilon L}{\mu} = \frac{\upsilon L}{\nu}$$

2.60×10^5 is Reynolds number for lotus-inspire airfoil, this means that the airflow around the airfoil is laminar.

3.2 Experimental Results

The conducted experiment simulated real life conditions, as wind speed was 12 m/s and with an optimal room temperature and pressure. The results are demonstrated in the table below.

Table 2
Present experimental results

	NACA airfoil blade	Lotus-Inspired blade
Trial 1	2.84 watt	3.62 watt
Trial 2	2.91 watt	3.70 watt
Trial 3	2.69 watt	3.77 watt
Average	2.81 watt	3.7 watt

It is clear from Table 2 that the output power of the Lotus-inspired turbine model is higher than the output power of the NACA-blade turbine model by about 31.7%. Thus, the Lotus-inspired wind turbines can be utilized in small and medium-scale projects with average or below average wind speed.

4. Conclusions

Based on the above illustrations, results and discussions, the following concluding points can be stated

- The output power of the Lotus-inspired turbine model is higher than the output power of the NACA-blade turbine model by about 31.7%.
- The Lotus-inspired wind turbines can be utilized in small and medium-scale projects.
- 3D-printer proved to be an effective tool in manufacturing small-scale wind turbines.
- CFD investigation is immensely helpful in understanding the details of the aerodynamics of the turbine blade.

Therefore, some points may be recommended for further investigations such as

- Manufacturing and testing of larger turbines with different materials for better understanding of their performance.
- Testing the turbine blade at different angles of attack (0°-20°).
- Testing different blades featuring other NACA airfoils in comparison to the Lotus-inspired blades.
- Using a suitable generator for better output power.

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References
[1] Gielen, Dolf, Francisco Boshell, Deger Saygin, Morgan D. Bazilian, Nicholas Wagner, and Ricardo Gorini. "The role of renewable energy in the global energy transformation." *Energy Strategy Reviews* 24 (2019): 38-50. https://doi.org/10.1016/j.esr.2019.01.006

[2] Bahrampour, Hamid, Amir Khosro Beheshti Marnani, Mohammad Bagher Askari, and Mohammad Reza Bahrampour. "Evaluation of renewable energies production potential in the Middle East: confronting the world's energy crisis." *Frontiers in Energy* 14, no. 1 (2020): 42-56. https://doi.org/10.1007/s11708-017-0486-2

[3] Dixon, S., and C. Hall. "Wind Turbines." *Fluid Mechanics and Thermodynamics of Turbomachinery* (2014): 419-485. https://doi.org/10.1016/B978-0-12-415954-9.00010-3

[4] Herreraa, Camilo, Mariana Correaa, Valentina Villadaa, Juan D. Vanegasb, Juan G. Garcıaa, César Nieto-Londonoa, and Julián Sierra-Péreza. "Structural Design and Manufacturing Process of a Low Scale Bio-Inspired Wind Turbine Blades." *Composite Structures* 208 (2018): 1-12. https://doi.org/10.1016/j.compstruct.2018.08.061

[5] Chu, Yung-Jeh, and Wen-Tong Chong. "A biomimetic wind turbine inspired by Dryobalanops aromatica seed: Numerical prediction of rigid rotor blade performance with OpenFOAM®." *Computers & Fluids* 159 (2017): 295-315. https://doi.org/10.1016/j.compfluid.2017.10.012

[6] Krogstad, P-Å., and J. A. Lund. "An experimental and numerical study of the performance of a model turbine." *Wind Energy* 15, no. 3 (2012): 443-457. https://doi.org/10.1002/we.482

[7] Ikeda, Teruaki. "Study on noise-reduction and high-efficiency of bird wing-inspired micro-wind turbines." *PhD diss., 千葉大学= Chiba University*, 2018.

[8] Miklosovic, D. S., M. M. Murray, L. E. Howle, and F. E. Fish. "Leading-edge tubercles delay stall on humpback whale (Megaptera novaeangliae) flippers." *Physics of Fluids* 16, no. 5 (2004): 39-42. https://doi.org/10.1063/1.1688341

[9] Fish, Frank E., Paul W. Weber, Mark M. Murray, and Laurens E. Howle. "The Tubercles on Humpback Whales' Flippers: Application of Bio-Inspired Technology." *Integrative and Comparative Biology* 51, no. 1 (2005): 203-213. https://doi.org/10.1093/icb/icr016

[10] Seidel, Cory, Sanjay Jayaram, Leah Kunkel, and Alexander Mackowski. "Structural analysis of biologically inspired small wind turbine blades." *International Journal of Mechanical and Materials Engineering* 12, no. 1 (2017): 1-9. https://doi.org/10.1186/s40712-017-0085-3

[11] El-Hadidi, M. N. "Distribution of Cyperus papyrus L. and Nymphaea lotus L. in inland waters of Egypt." *Munich Bot Staatssamml Mitt* (1971).

[12] Hegazy, Ahmad K., W. M. Amer, and A. A. Khedr. "Allelopathic effect of Nymphaea lotus L. on growth and yield of cultivated rice around Lake Manzala (Nile Delta)." *Hydrobiologia* 464, no. 1 (2001): 133-142. https://doi.org/10.1023/A:1013943318230

[13] Mohamed, Zein A., and Mamdouh S. Serag. "Ecology and anatomy of Nymphaea Lotus L. in the Nile delta." *Journal of Environmental Sciences* 26, no. 2 (2003): 1-20.

[14] Ayyad, S. Egyptian plants. *A photographic Guide: Part 1: Trees, Shrubs, Ornamentals, Weeds, and Desert Plants*. Akhbar El-Youm Press, 1999.

[15] Ansys. "Free Student Software: ANSYS Student." *ANSYS, Inc*. Accessed March 25, 2021. https://www.ansys.com/academic/free-student-products.

[16] Ultimaker. "Ultimaker 2+: Robust single extrusion." *Ultimaker BV*. Accessed August 11, 2020. https://ultimaker.com/3d-printers/ultimaker-2-plus.

[17] Loutun, Mark Jason Thomas, Djamal Hissein Didane, Mohd Faizal Mohideen Batcha, Kamil Abdullah, Mas Fawzi Mohd Ali, Akmal Nizam Mohammed, and Lukmon Owolabi Afolabi. "2D CFD Simulation Study on the Performance of Various NACA Airfoils." *CFD Letters* 13, no. 4 (2021): 38-50. https://doi.org/10.37934/cfdl.13.4.3850

[18] Sarkar, Shivananda, and Shaheen Beg Mughal. "CFD Analysis of Effect of Flow Over NACA 2412 Airfoil Through the Shear Stress Transport Turbulence Model." *International Journal of Mechanical and Production Engineering* 5, no. 7 (2017): 2320-2092.