UDC 551.556.3:621.548.5 (045)

[1]V. M. Sineglazov,
[2]A. A. Ziganshin

OPTIMAL PITCH ANGLES OF DARIEUS H-ROTOR BLADES

Aviation Computer-Integrated Complexes Department, National Aviation University, Kyiv, Ukraine
E-mails: [1]svm@nau.edu.ua, [2]anwarzihan@gmail.com

Abstract**—***Vast survey of investigations to determine the optimal pitch angles for Darrieus H-rotor blades was implemented. Wind tunnel tests were done for a four bladed rotor. It was shown that there was the pitch angle providing the better power and torque characteristics.*

Index Terms—Angle of attack; tip speed ratio; power and torque coefficients.

I. INTRODUCTION

Wind power is to be a vital source of environmental-friendly energy and becomes more important in the recent years. Development and improvement of alternative energy sources is an urgent problem for Ukraine. Three-bladed horizontal-axis propeller type wind turbines (windmills) are widespread in the world. This is due to their high rate of wind energy use. As for the vertical axis wind turbines (VAWT) only a Darrieus rotor has the close values of the power efficiency. However, VAWT are capable of producing a lot of power and offer many advantages for small-scale and domestic applications. Small scale VAWTs show potential for urban rooftop installations where they can capture the highly unstable, turbulent wind flow patterns which are typical in an urban environment. Being axisymmetric, they are omni-directional turbines which respond well to changes in wind direction, unlike their horizontal counterparts.

The drawback of Darrieus type VAWT is their inability to reliably self-start at low tip speed ratios (TSR). The starting torque may be very low and even negative at low TSRs. Therefore, one way is having a special motor to start the rotor. Another way is combining it with Savonius rotor operating well at low TSRs (about 1). The design TSR λ for Darrieus rotor may not be taken lower than about 4 because of that it results in stalling of the blade as it moves about square to the wind at lower values of λ. The design TSR λ may not be taken higher than about 7 because of that it results in too high C_D/C_L (drag to lift ratio) at higher values of λ.

Since the blade has a positive angle of attack α at the front side of the rotor and a negative angle α at the back side, one has to use symmetrical airfoils. These airfoils have lower maximum lift coefficients if compared with asymmetrical airfoils of the same thickness.

For the low values of TSR (about 4 and less) the pitch angle β at which a symmetrical airfoil stalls depends on the relative airfoil thickness and on the Reynolds value. The airfoil NACA 0015 already stalls at 11° and $\mathrm{Re}=1.66\cdot 10^5$. Therefore, one needs thick airfoils at low Reynolds values which occur at low chords and low wind speeds. However thick airfoils have higher minimum C_D/C_L values than thin ones and this has an unfavourable influence on the value of power coefficient C_P.

Besides, it is difficult to protect the H-rotor turbine against high wind speeds. Braking the vertical shaft mechanically to turn the turbine out of the wind is the only possibility, but it is not really fail safe because the turbine will turn unloaded if the brake fails for some reason. Impairing the efficiency of the turbine with the pitch control maybe the only possible way to escape but it requires a complicated construction.

II. REVIEW OF PREVIOUS INVESTIGATIONS

South and Rangi [1], performed a wind tunnel investigation of a 4.27 m diameter Darrieus H-rotor. The 2-bladed rotor had a solidity $\sigma=0.07$, and chord ratio $c/r = 0.07$. It was noted an increase in C_P of 11% when their blades were offset from an initial pitch $\beta = -4°$ (toe-out) to a pitch of $\beta = 0°$.

Klimas and Worstell [2], investigated the effects of blade offset on a 5 m diameter Darrieus H-rotor with $\sigma = 0.22$, and $c/r = 0.06$. Using a geometric analysis presented later, that relates blade offset with equivalent preset pitch, they observed power increases of 3% for blade pitch angles up to $\beta = -2°$.

The effect of some design parameters such as, pitch angle and airfoil type was experimentally investigated by Kinloch Kirke [3]. He studied ways for self starting of the rotor, performance prediction and the different parameters of airfoil which affect the performance. It was shown that increasing in power coefficient may be achieved with thick airflows.

Paraschivoiu [4] reported predictions of the effects of preset pitch on the performance of a low solidity H-rotor. His results indicate increases in predicted power of 5% for a preset of $\beta = -2°$.

Jon De Coste [5] made model of H-rotor using NACA 0012 profile to evaluate the performance. It was found that the rotor performs well at certain TSR. At starting it faces negative torque which is referred as “dead band” in which low or negative torque makes unable to start.

Armstrong, Gosselin et al. [6], [7] showed with various experiments that, at least for high solidity cases, changing the pitch angle β from 0° to a small toe-out angle increased the efficiency of the rotor.

Fiedler et al. presented [8] the results of wind tunnel tests on a high solidity H-rotors. Preset pitch configurations of ± 3.9° and ± 7.8° were tested and results show performance increases of up to 29% with a toe-out configuration. The value of TSR at peak power was observed to remain relatively constant for changes in preset pitch. These phenomena were observed for NACA 0015 and NACA 0021 blade profiles; however, the NACA 0021 profile resulted in improved performance over a broader range of TSRs. In general, imposing a toe-in preset pitch resulted in dramatically decreased VAWT performance, whereas toe-out preset pitch was seen to improve overall performance.

Paraschivoiu et al. [9] also studied the optimal variation of the blades pitch angles of an H-rotor that maximizes its torque at given operational conditions. They found that the optimized variable pitch leads to an improvement in C_P compared to 0° pitch angle of about 21% at wind speed of 7.3 m/s and rotational speed of 125 rpm. At higher wind speeds (above 9 m/s) it results in a decrease of the turbine power.

Samanoudy et al. [10] investigated the VAWT performance with varying the design parameters such as pitch angle, number of blades, airfoil type, rotor radius and blades chord length. It has been found that the pitch angle as the other parameters has a significant effect on C_P. The maximum value of C_P obtained in this research was 25% using rotor radius of 40 cm, chord length of 15 cm, pitch angle of 10°, airfoil type NACA 0024. Four blades case was found to be the best configuration in this study. The obtained maximum power coefficient was for the pitch angle of about 10°.

Payam Sabaeifard et al. [11] also did computational and experimental study of the aerodynamics and performance of small scale Darrieus H-rotor and as a result, it has been found that a 3-bladed rotor with 35% solidity has the best self-starting ability and efficiency among all geometries.

Vast analysis with 2D and 3D simulations conducting with the effect of pitch angle to the performance of VAWT was produced by Gosselin R. et al. [12]. It was shown that setting of a small toe-out angle improves the efficiency of the turbine for the case at $\lambda = 3$. A small amount of toe-out to the blade reduces the angle of attack in the upstream phase, and increases it in the downstream one. Both are good for a Darrieus rotor, as the angles of attack are too high in the first pass due to the free stream velocity, and too low (in negative values) in the second one due to the velocity deficit. It was noted that the optimal angle of attack is around 9 degrees, close to the maximal lift to drag ratio of the profile. It was assumed that it is necessary to double the angles of attack (up to –18 degrees) in the downstream phase of the cycle. Simulation results for fixed, non-zero pitch angle cases show that there is a great potential of improvement in “medium” TSR (from 2 to 4) for rotor with solidity around 0.5. This opens the way to dynamic pitch control, with the ability to maximize blade lift to drag ratio over a complete cycle. The parametric study showed that the most efficient fixed pitch angles are those with solidity about $\sigma = 0.2$, which is consistent with the experimental data available. Higher solidity rotors can’t reach the same level of effectiveness without blade pitch control, but the first tests with pitch control confirm there is an improvement potential, with up to 27% relative efficiency gain close to the Betz limit.

Hiren Tala [13] on the base of CFD simulations (by using FLUENT in ANSYS Workbench 14) showed that the optimal power output with fixed pitch angle for the airfoil NACA 0012 can be determined at 8 degrees of the pitch angle.

III. PROBLEM STATEMENT

A Darrieus H-rotor, as well as all of the VAWTs, operates on the principle of lift to generate torque. As the rotor rotates, the vector summation of the incoming wind velocity with the rotational velocity of the blade creates an angle of attack, resulting in a lift force. When broken down into components, the thrust component contributes to the rotor rotation, whereas the fluctuating radial component can lead to rotor vibration and blade fatigue (Fig. 1). Both a rotational velocity component and an external wind velocity are required in order to have sustained rotation. The blade preset pitch angle β is defined as the angle between the blade chord and the tangent to the swept arc at the mount point, as shown in Fig. 2. [8].

So we have to find the pitch angle β providing the maximum of power coefficient C_P over the wide range of TSR λ:

$$\max_{\beta} C_P(\beta,\lambda).$$

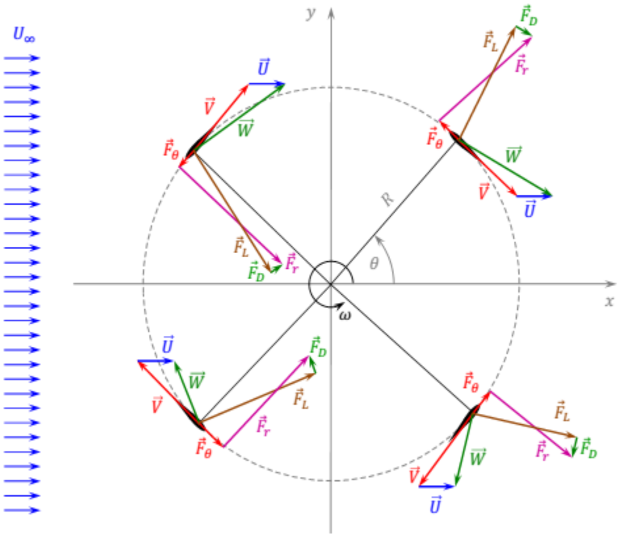

Fig. 1. Velocity and force triangles at different positions of the blade for λ >1

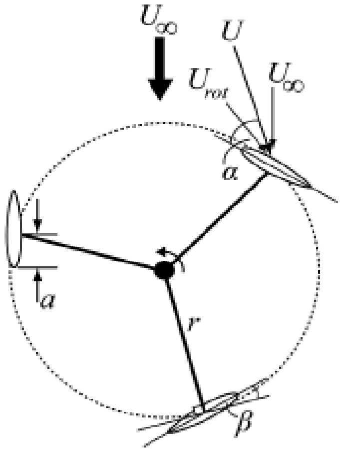

Fig. 2. Plan view of rotor showing the preset blade pitch angle β, angle of attack α, the incident wind speed due to U_∞ and rotational speed U_{rot}, and mount location offset *a*

III. PROBLEM SOLUTION

As it was said before the H-rotor had a problem of self-starting and had unsufficiently acceptable power at low speeds of wind.

As for rotors that have high solidity *c/r* ratios when the rotor spins the leading edge of the blade experiences a negative angle of attack (AOA), the centre will see an effective 0° AOA, and the trailing edge results in a positive AOA (Fig. 2). That is why the high solidities should be out of the consideration.

Three modifications for variable pitch control to improve the performance of the rotor were studied by Staelens et al. [14] (Fig. 3). They examined the performance of a H-rotor when the local angle of attack is kept just below the stall value throughout its cycle of rotation. This is accomplished by adjusting the local geometric angle of attack of the blade. This modification results in a very significant increase in the power output for wind speeds above 10 m/s. However, this modification requires sharp changes (jumps) in the local angle of attack making it physically and mechanically impossible to realize. Here they replaced the local geometric angle of attack by the local profile stall angle.

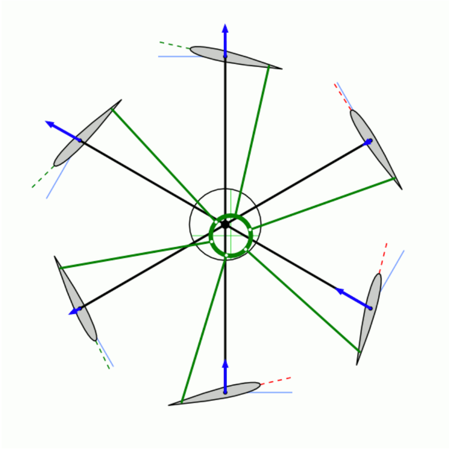

Fig. 3. Example of rotor with pitch control

Also the performance characteristics of H-rotor with the controlgear of blades were studied by Grinchenko et al. [15] (Fig. 4). The results of experimental researches in a hydrotray and a wind tunnel showed the self start of the rotors at low speeds of the incoming flow, a significant increase in both of the flow energy and the torque moment, and a decrease of the wind loads on the shaft in comparison with the preset blades H-rotors.

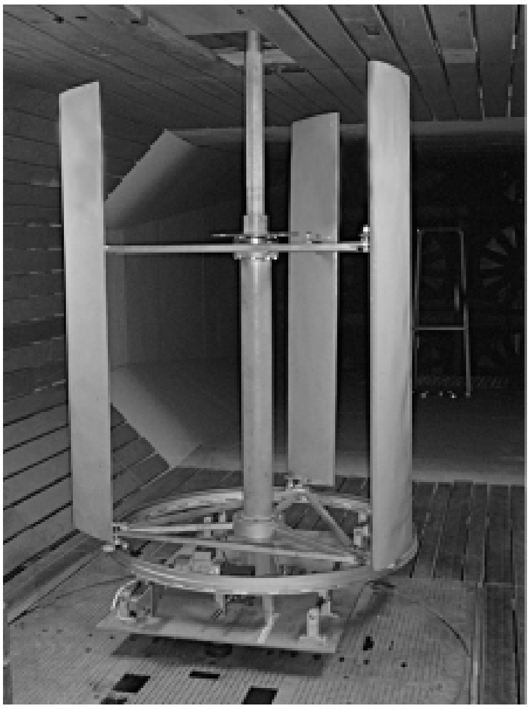

Fig. 4. Rotor with pitch control mechanism of blades

Four bladed Darrieus H-rotor (Figs 5–8) with the height of 400 mm and the diameter of 260 mm was tested in the wind tunnel with various values of TSR. Length of chord with airfoil NACA 0018 was 100 mm and offset from the leading edge was 30 mm. The blades with symmetric airfoil were done from polymer and wrapped in with one layer cloth that was sticked to the polymer with glue. Besides it was equipped with endplates with the diameter of 290 mm and with the thickness of 2 and 3 mm. Two ball bearings were mounted on the both ends of the rotor. The stepping motor (Fig. 5) was applied as the generator which was attached to the top end of the shaft with the diameter of 12 mm.

IV. RESULTS

The dependences of torque and power coefficients versus TSR were presented in Figs 9 and 10. It was seen that the value of pitch angle of about 10 degrees brings the better torque and power characteristics. It is possible to assert that the proper choice of the pitch angle can bring the increase of the torque and power coefficients.

V. CONCLUSIONS

It is possible to conclude that pitch angle of 10 degrees shows the better torque and power characteristics over a broad range of TSR.

Also we can make a Darrieus rotor to self start by introducing a cyclic variation of the blade pitch angle. However, this requires a rather complicated control mechanism with many turning points and the advantage having the omni-directional feature is lost.

Fig. 5. Darrieus rotor to be tested

Fig. 7. Pitch angles to to be set

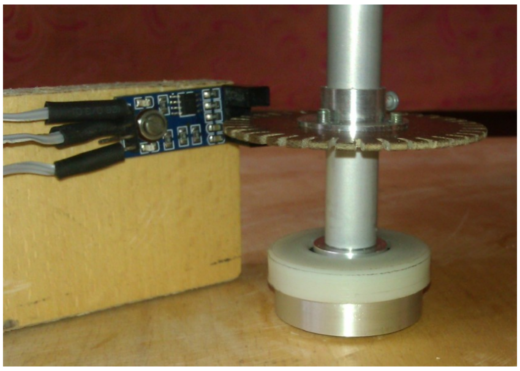

Fig. 6. Optocouple to measure the speed of rotation

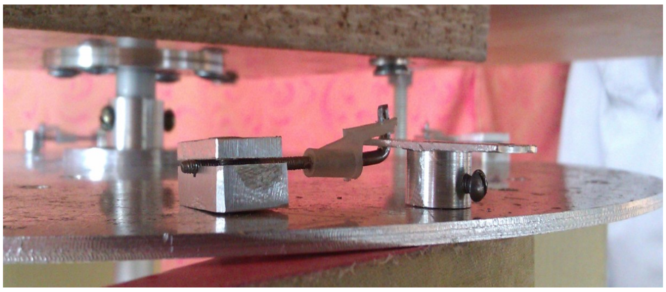

Fig. 8. Kinematics to vary and fix the pitch angles

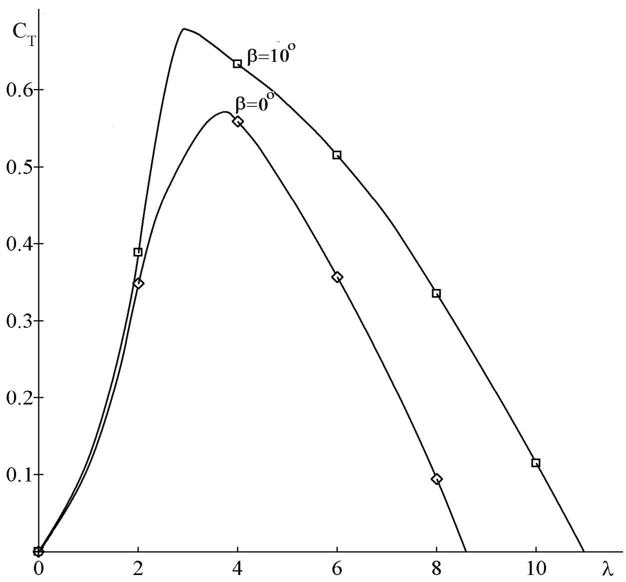

Fig. 9. Torque coefficient versus TSR

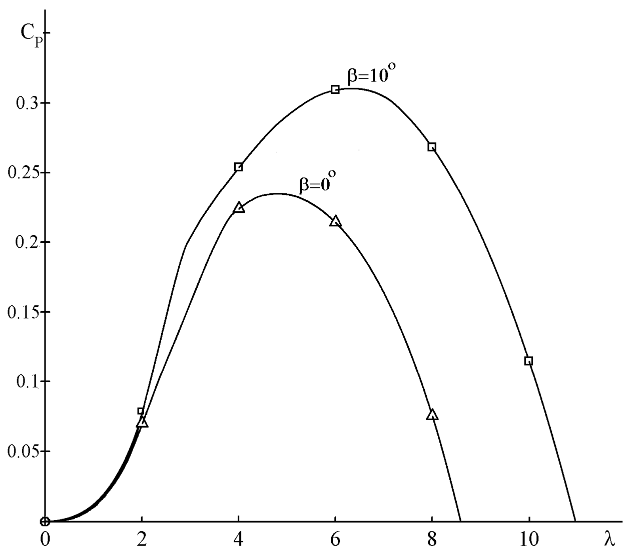

Fig. 10. Power coefficient versus TSR

REFERENCES

[1] P. South and R. S. Rangi, "A Wind Tunnel Investigation of a 14ft. Diameter Vertical Axis Windmill," Low Speed Aerodynamics Laboratory (Canada) Laboratory Technical Report, National Aeronautical Establishment, LTR-LA-105, 1972.

[2] P. Klimas and M. Worstell, "Effects of Blade Preset Pitch/Offset on Curved-Blade Darrieus Vertical Axis Wind Turbine Performance," Sandia National Laboratories, SAND-81-1762, Albuquerque, NM, 1981.

[3] K. B. Kirke, "Evaluation of self-starting vertical axis wind turbines for stand-alone applications," Ph.D. thesis, Griffith University, Brisbane, Australia, 1998.

[4] I. Paraschivoiu, "Wind Turbine Design with Emphasis on Darrieus Concept," *Polytechnic International Press*, Montreal, 2002, 346–349.

[5] J. De Coste, D. McKay, B. Robinson, S. Whitehead, and S. Wright. Design Project Vertical Axis Wind Turbine, Thesis, Dalhousie University, Dec 2005.

[6] S. Armstrong, A. Fiedler, and S. Tullis. "Flow separation on a high reynolds number, high solidity vertical axis wind turbine with straight and canted blades and canted blades with fences," *Renewable Energy*, vol. 41, pp. 13–22, 2012.

[7] R. Gosselin, "Control of flow separation on vertical axis wind turbine blades," Master's thesis, Departement of Mechanical Engineering, University of Sheffield, September 2008.

[8] A. J. Fiedler, and S. Tullis, "Blade Offset and Pitch Effects on a High Solidity Vertical Axis Wind Turbine,"*Wind Engineering.* vol. 33, no. 3, pp. 237–246. 2009.

[9] I. Paraschivoiu, O. Trifu, and F. Saeed, "H-Darrieus wind turbine with blade pitch control," *Int J. Rotat Mach* 2009; Article ID 505343.

[10] M. El-Samanoudy, A. A. E. Ghorab, and Sh. Z. Youssef, "Effect of some design parameters on the performance of a Giromill vertical axis wind turbine," *Ain Shams Engineering Journal*, pp. 85–95, 2010.

[11] P. Sabaeifard, H. Razzaghi, and A. Forouzandeh, "Determination of Vertical Axis Wind Turbines Optimal Configuration through CFD Simulations." *International Conference on Future Environment and Energy*, 2012, pp. 109–113.

[12] R. Gosselin, G. Dumas, and M. Boudreau, "Parametric study of H-Darrieus vertical-axis turbines using uRANS simulations." Paper CFDSC-2013 #178, Session 13–6 - *Rotating Machine I, 21st Annual Conference of the CFD Society of Canada*, Sherbrooke, Canada, May 6–9, 2013, pp.1–16.

[13] H. Tala, "Simulations of Small Scale Straight Blade Darrieus Wind Turbine Using Latest CAE Techniques to get Optimum Power Output." *International Journal of Advance Foundation and Research in Science & Engineering (IJAFRSE),* vol. 1, Issue 5, October 2014. Impact Factor: 1.036, Science Central Value: 10.33. pp. 46–58.

[14] Y. Staelens, F. Saeed, and I. Paraschivoiu, "A straight-bladed variable-pitch VAWT concept for improved power generation," *41st Aerospace sciences meeting*, AIAA-2003-0524, 2003.

[15] V. T. Grinchenko, V. P. Kayan, and V. A. Kochin, "Investgations and optimization of operating characteristics of vertical axis wind rotor with blades control-gear," *Reports of the National Academy of Sciences of Ukraine*, no. 12, pp. 62–68, 2008.

Received December 16, 2015

Sineglazov Viktor. Doctor of Engineering. Professor.
Aviation Computer-Integrated Complexes Department, National Aviation University, Kyiv, Ukraine.
Education: Kiev Polytechnic Institute. Kiev, Ukraine (1973).
Research interests: Air Navigation, Air Traffic Control, Identification of Complex Systems, Wind/solar power plant.
Publications: more than 500 papers.
E-mail: svm@nau.edu.ua

Ziganshin Anwar. Asistant.
Aviation Computer-Integrated Complexes Department, National Aviation University, Kyiv, Ukraine.
Education: Kazan Aviation Institute. Kazan, Russia (1978).
Research interests: computer aided design systems, numerical methods of aerodynamics, renewable sources of energy.
Publications: 8.
E-mail: anwarzihan@gmail.com

В. М. Синєглазов, А. А. Зіганшин. Оптимальні кути установки лопатей ротора Дар'є

Представлено широкий огляд досліджень, присвячених визначенню оптимальних кутів установки лопатей Н-роторів Дар'є. Проведено випробування в аеродинамічній трубі для чотирьох-лопатевого ротора. Показано, що існують кути установки, що забезпечують кращі характеристики за потужністю і обертальним моментом.

Ключові слова: кут атаки, швидкохідність, коефіцієнти потужності і крутного моменту.

Синєглазов Віктор Михайлович. Доктор технічних наук. Професор.
Кафедра авіаційних комп'ютерно-інтегрованих комплексів, Національний авіаційний університет, Київ, Україна.
Освіта: Київський політехнічний інститут. Київ, Україна (1973).
Напрям наукової діяльності: аеронавігація, управління повітряним рухом, ідентифікація складних систем, вітроенергетичні установки.
Кількість публікацій: більше 500 наукових робіт.
E-mail: svm@nau.edu.ua

Зіганшин Анвар Абдуллович. Асистент.
Кафедра авіаційних комп'ютерно-інтегрованих комплексів, Національний авіаційний університет, Київ, Україна.
Освіта: Казанський авіаційний інститут. Казань, Росія (1978).
Напрям наукової діяльності: системи автоматизації проектувальних робіт, числові методи в аеродинаміці, поновлювальні джерела енергії.
Кількість публікацій: 8.
E-mail: anwarzihan@gmail.com

В. М. Синеглазов, А. А. Зиганшин. Оптимальные углы установки лопастей роторов Дарье

Представлен обширный обзор исследований, посвященных определению оптимальных углов установки лопастей Н-роторов Дарье. Проведены испытания в аэродинамической трубе для четырех-лопастного ротора. Было показано, что существуют углы установки, обеспечивающие лучшие характеристики по мощности и крутящему моменту.

Ключевые слова: угол атаки, быстроходность, коэффициенты мощности и крутящего момента.

Синеглазов Виктор Михайлович. Доктор технических наук. Профессор.
Кафедра авиационных компьютерно-интегрированных комплексов, Национальный авиационный университет, Киев, Украина.
Образование: Киевский политехнический институт. Киев, Украина (1973).
Направление научной деятельности: аэронавигация, управление воздушным движением, идентификация сложных систем, ветроэнергетические установки.
Количество публикаций: больше 500 научных робот.
E-mail: svm@nau.edu.ua

Зиганшин Анвар Абдуллович. Асистент.
Кафедра авиационных компьютерно-интегрированных комплексов, Национальный авиационный университет, Киев, Украина.
Образование: Казанский авиационный институт. Казань, Россия (1978).
Направление научной деятельности: системы автоматизированного проектирования, численные методы в аэродинамике, возобновляемые источники энергии.
Количество публикаций: 8.
E-mail: anwarzihan@gmail.com