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[1]O. I. Zhdanov,
[2]O. A. Sushchenko,
[3]V. V. Orlianskyi

RESEARCH OF AERODYNAMIC AIRFOIL WITH VORTEX CENERATORS IN WIND TUNNEL

[1,3]Aerospace Faculty, National Aviation University, Kyiv, Ukraine
[2]Faculty of Air Navigation, Electronics and Telecommunications, National Aviation University, Kyiv, Ukraine
E-mails: [1]azhdanov@nau.edu.ua ORCID 0000-0001-5273-571X,
[2]sushoa@ukr.net ORCID 0000-0002-8837-1521, [3]aerodyn@nau.edu.ua ORCID 0009-0000-8186-4211

Abstract—*This article deals with researching the aerodynamic airfoil model in the wind tunnel using volume vortex generators. The volumetric vortex generators of three types for the definite blowing model are described including their geometrical characteristics. The features of volume vortex generators mounting on the surface of the aerodynamic airfoil model are represented. Features of the experiment in the wind tunnel are described. Comparative changes in aerodynamic characteristics of the aerodynamic airfoil model with and without volume vortex generators in the form of graphical dependencies have been shown. The comparison has been made for different values of Re numbers. The analysis of the obtained dependencies has carried out. The visualization of airflow in an experimental way is illustrated. The results are directed at improving the aerodynamic characteristics of unmanned aerial vehicles. The main significance of the research lies in improving the behavior of unmanned aerial vehicles in the area of critical angles of attack. The obtained results can also be useful for aircraft of the wide class.*

Index Terms—Airfoil section; volume vortex generator; wind tunnel; aerodynamic characteristics; aerodynamic quality; experiment.

I. INTRODUCTION AND PROBLEM STATEMENT

The problem of expanding the range of angles of attack for the safe operation of unmanned aerial vehicles (UAVs) by eliminating the phenomenon of stalling by controlled separation of the airflow on the wing and control bodies in subsonic flight modes by installing volume vortex generators (VVG) on the leading edge of the wing and optimizing the geometric parameters of their shape and the location is of considerable scientific and practical interest.

The purpose of this work was to study the possibility and effectiveness of using an artificially created organized system of large longitudinal vortices by modifying its space-time scales, as well as the development of a practical approach to the generation of large longitudinal vortices on the surface of an aerodynamic profile model. Research studies in this direction have shown the effectiveness of using VVG and even led to using such a term as a vortex-active wing or, more broadly, a vortex-active aerodynamic surface [1], [2].

The research method represents an experimental weight test of the profile model in the wind tunnel (WT) and a comparative analysis of their results in the form of changes in integral aerodynamic characteristics.

The experiments were carried out in a low-velocity closed-type aerodynamic atmospheric tube with an open working part of an elliptical cross-section with the dimensions of the axes 750×420 mm and a length of 900 mm. The airflow speed is 3.5...30 m/s. The air tube is equipped with an external three-component Reiter's aerodynamic weight, which provides the measurement of three components of the total aerodynamic force, which allows calculating the dependence of dimensionless aerodynamic coefficients on the angle of attack $c_{xa}, c_{ya}, m_{z1} = f(\alpha)$. The built-in α-mechanism for changing the angular position of the model provides a change in the angle of attack of the model in the range α = –200... +400 degrees.

The suspension of the model in the working part of the wind tunnel provides the possibility of circular blowing of the model at the angle of attack in separate areas within the available range of changing the angular position of the model [3] – [6]. The mechanical system for decomposing the forces of the Reiter scale can be connected to the system of tensor converters of weight loads on weight components into electrical signals. The strain gauge system provides automation of the process of measurement and recording of test results during changes in the angular position of the model, display of measurement results in the form of dependences of aerodynamic coefficients on the angle of attack on the display screen during the experiment [7] – [9].

II. Research of Aerodynamic Surface Model

As the researched model of the aerodynamic surface, the model of the classical symmetrical aerodynamic airfoil NACA0012 is chosen. It is often used in similar experiments. The blowing model has a rectangular shape, the span of the model is 350 mm, the chord is 175 mm, the area is 0.06125 m^2, the geometric elongation is $\lambda = 2$, the longitudinal axis of the model is located at a distance of 25% of the length of the chord or 0.04375 m from the toe.

Vertical screens are installed on the sides of the profile model, which ensures a large effective elongation of the model ≈ 10. Such a layout of the model makes it possible to single out the influence of the artificially created structure of longitudinal vortices with the help of VVG on the profile resistance of the profile model, primarily pressure resistance, as well as friction, without taking into account the inductive component from the influence of finite vortices.

The model of the aerodynamic profile is composed of models of VVG, which are installed in the model's toe. Based on information on the use of various types of vortex generators, turbulators, generators, aerodynamic inflows, and other means of influencing and controlling vortex structures, the three types of VVG were created. They are shown in Fig. 1 in three different projections [8].

The first type of VVG has a spindle-like elongated shape, the source of vortex generation is the joint of the VVG and the airfoil section, as well as the side surface of the VVG itself.

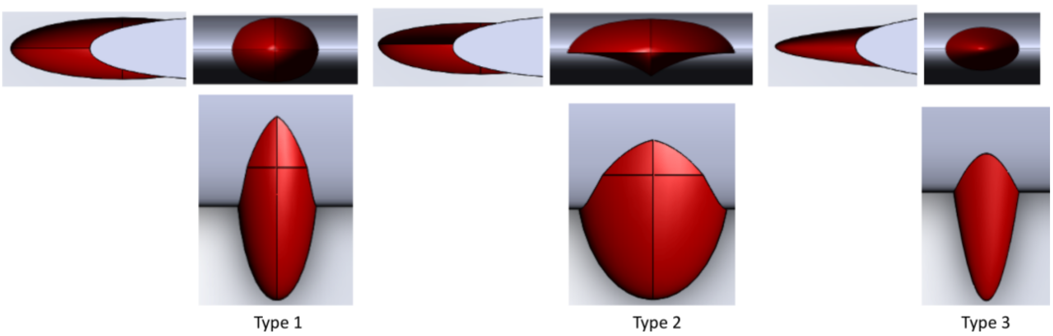


Fig. 1. Volumetric vortex generators of three types for the NACA0012 aerodynamic airfoil model

The second type of VVG has a vertically flattened shape with sharp front and side edges of an arched shape. The source of vortex formation is used as the joint. Undercuts are made on the lower surface of the VVG to increase the vortex-generating and load-bearing properties of the VVG.

The third type of VVG also has a flattened shape but is symmetrical about its median plane, and when viewed from above has a triangular outline with a rounded nose and a rounded lateral edge. The opening angle of the cone is 28 degrees, and the source of the generation of longitudinal vortices is the junction of the VVG with the profile and the side edge of the VVG.

The chosen forms of VVG generate longitudinal vortices of different intensities and with various spatial and temporal characteristics [10] – [12]. In addition to the shape of the VVG, the factors affecting the characteristics of the generation of the system of longitudinal vortices were the size of the VVG, their number, and the geometric parameters of the layout.

The dimensions of the VVG installed on the aerodynamic airfoil model can be changed by pushing the VVG on the section or by scaling the dimensions of the VVG. In the first case, the extension of the VVG from the toe of the section by a certain amount is simulated. In the second case, the installation of the VVG of a certain size is simulated [13] – [15]. The general geometric parameters of the VVG layout of various shapes and sizes will be the area of the VVG that protrudes beyond the front edge of the section, the length of the protrusion, the length of the front edge of the section covered by the VVG, the angle of installation of the VVG (the angle between the chords of the VVG and the section), and the installation step of the VVG by scale of the model. The specified geometric parameters of the VVG and their location in absolute values attributed to the model's dimensions can be useful during the analysis of the effectiveness of the effect of vortex generation on the aerodynamic characteristics of the airfoil section.

Tests of the section model were carried out for three values of the average speed of the airflow in the working part of the wind tunnel such as $V \approx 9$ m/s, 18 m/s, and 27 m/s, which correspond to the numbers Re ≈ 100000, 200000, and 300000, respectively. The airflow quality was characterized by an average degree of turbulence $\varepsilon \approx 3.5\%$ at $V = 9$ m/s, $\varepsilon \approx 2\%$ at

$V = 18$ m/s, and $\varepsilon \approx 1\%$ at $V = 27$ m/s. The geometric angle of attack of the model varied in the range from –5 to 34 degrees, in some versions of the tests from 5 to 44 degrees, and covered large closed angles of attack. The real angle of attack was calculated taking into account the geometric and inductive bevel of the airflow in the working part of the wind tunnel. The results of the experiment are the real angles of attack and the angles of attack of the α-mechanism, the results of measurements of aerodynamic coefficients and airflow speed, calculated as the average values of multiple measurements at a given angular position of the model, and the statistical characteristics of the measurements in the form of root mean square deviations [9], [10].

III. Analysis of Research Results

The analysis of the effect of the installation of the VVG on the aerodynamic characteristics of the NACA0012 aifoil section model was carried out by comparing the dependences of the aerodynamic coefficients as a function of the angle of attack for a clean profile and a profile with installed vortex generators, plotted on the same graph [12], [13]. Although the dependences of the aerodynamic coefficients characterize the change in the total loads, they are quite informative to clarify the differences in the behavior of the dependencies and put forward assumptions about the change in the structure of the flow around the upper surface of the model when reaching critical angles of attack and flow disruption. Figure 2 compares graphs of aerodynamic characteristics for the layout of the first type VVG model in the amount of 5 pieces, size 20%, installed with a step of 70 mm. The graphs make it possible to consider and analyze the main characteristic effects of the installation of VVG on the aerodynamic characteristics of the aerodynamic airfoil model. Figures 2(a, b) show the influence of VVG layout on the dependence $c_{ya} = f(\alpha)$. Figures 2(c, d) illustrate dependencies $c_{xa} = f(\alpha)$, and aerodynamic quality $K = f(\alpha)$. Figure 2e illustrates the dependence $c_{mz1} = f(\alpha)$. Figure 2f shows the influence of the airflow on the dependence $c_{ya} = f(\alpha)$.

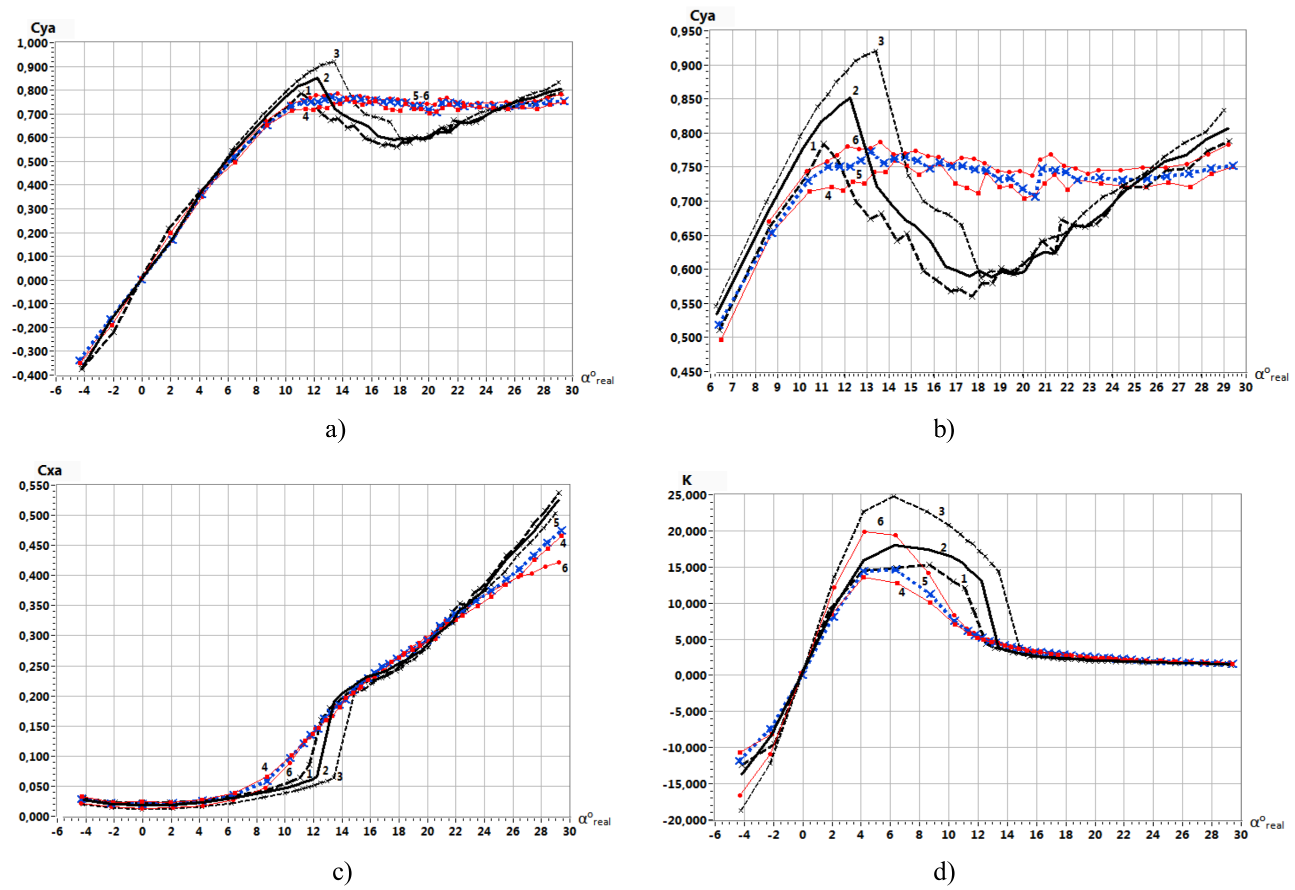
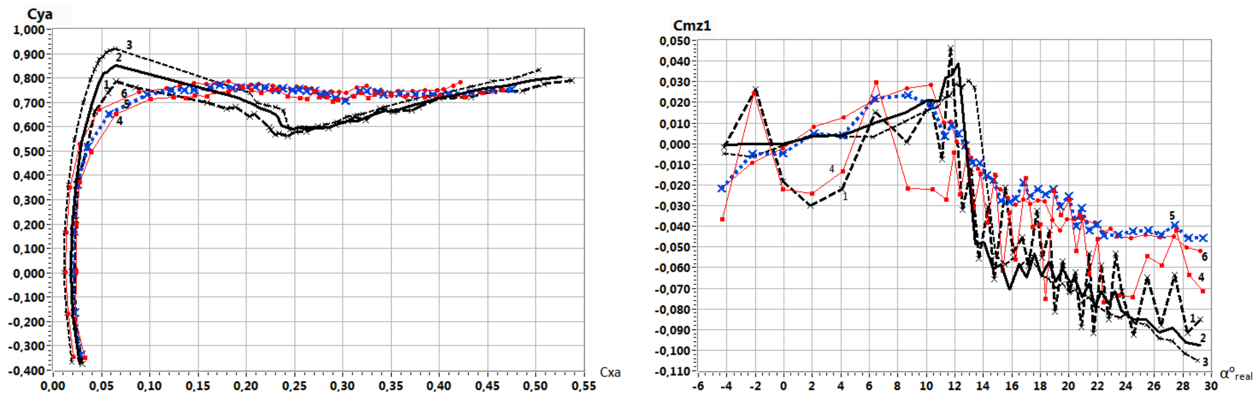


Fig. 2. Comparison of the influence of VVG on aerodynamic characteristics of the aerodynamic airfoil NACA0012: 1, 2, 3 without VVG for Re = 100000, 200000, 300000; 4, 5, 6 with VVG, type 1, relative size of the chord 20%, 5 pieces for Re = 100000, 200000, 300000; (a), (e) – turbulators V=18 m/s, relative size of the chord 7.5%; (b), (c), (d), (f) – section NACA0012, relative size of the chord 14%, step 70 mm, angle 10 degrees



e) f)

Fig. 2. Ending. (See also p. 72)

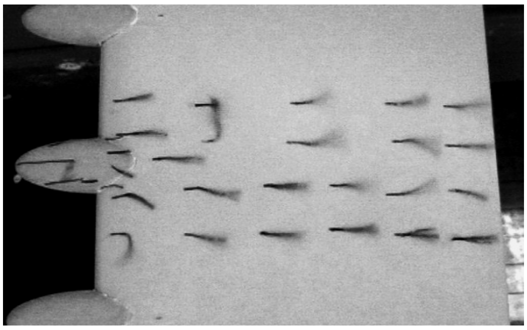
The analysis of the effect of the installation of the VVG on the aerodynamic characteristics of the NACA0012 profile model was carried out by comparing the dependencies of the aerodynamic coefficients as a function of the angle of attack for a clean profile and a profile with installed vortex generators, plotted on the same graph. Although the dependencies of the aerodynamic coefficients characterize the change in the total loads, they are quite informative in clarifying the differences in the behavior of the dependencies and put forward assumptions about the change in the structure of the flow around the upper surface of the model when reaching critical angles of attack and flow disruption. Figure 2 compares graphs of aerodynamic characteristics for the layout of the first type VVG model in the amount of 5 pieces installed with a step of 70 mm. The graphs allow us to consider and analyze the main effects of VVG installation on the aerodynamic characteristics of the airfoil model.

The comparison is made for three values of Re numbers. The graphs make it possible to make the main observations about the effect of the installation of the VVG on the separation characteristics, which are inherent to a greater or lesser extent to each type of VVG. First of all, let us note the significant decrease in the effect of the Re number on the change in the aerodynamic characteristics of the model in the area around the critical angles of attack and beyond critical angles of attack due to the installation of the VVG. The reason is the additional turbulence of the flow on the model's surface from the turbulators. Installation of turbulators eliminates the characteristic change in aerodynamic characteristics during flow disruption. This situation is characterized by a sharp decrease in lifting force after reaching a critical angle of attack. In the presence of an air conditioner, the lift coefficient reaches a certain constant level, which indicates the stability of the airflow structure, organized by superimposing a system of large longitudinal vortices on the flow structure of a clean profile at the critical angles of attack. As a result of this behavior of the lifting force, the sign of the critical angle of attack disappears. This level corresponds to the value for low speeds, in our case 9 m/s. At critical angles of attack, the structure of the flow becomes so stable that the lifting force becomes less than in the absence of VVG. But with an increase in the speed of the airflow, the change in the coefficient of lifting force occurs with the same gradient as in the absence of VVG.

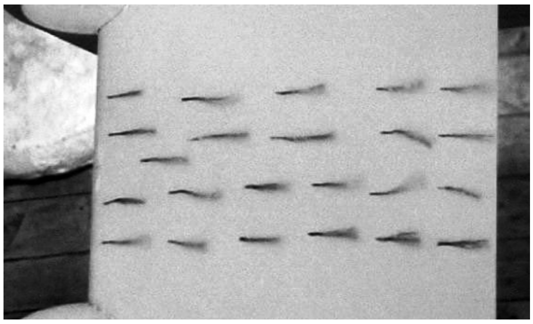
It is known that a sharp decrease in the lifting force after reaching the critical angle of attack is due to the occurrence of a global separation of the airflow on the upper surface of the profile model. Initially, the detachment of the turbulent boundary layer develops gradually with an increase in the angle of attack, the detachment line moves from the trailing edge of the profile towards the flow. On the dependence $c_{ya} = f(\alpha)$, this process is reflected in the appearance of non-linearity in its change. When the separation line approaches the line of maximum profile thickness, at some point, there is a jump-like transition of the separation line to the nose of the profile. Such a process is called global detachment, has an explosive uncontrolled nature, and spreads over the entire upper surface of the profile model. As a result, there are sharp changes in the behavior of dependencies $c_{ya} = f(\alpha)$, $c_{xa} = f(\alpha)$ on the aerodynamic characteristics graphs for the pure profile model, and they are especially noticeable in the behavior of the most sensitive characteristic $m_{z1} = f(\alpha)$.

Under the conditions of the presence of VVG, there is a smooth change in the angle of attack c_{xa} and longitudinal moment. Less resistance and higher aerodynamic quality at critical angles of attack in the conditions of the use of air defense systems. Turbulent separation in the presence of VVG begins at smaller angles of attack, judging by the earlier appearance of a characteristic nonlinearity in the behavior of the dependence $c_{ya} = f(\alpha)$, most likely due to increased turbulence of the boundary layer by longitudinal vortices from the VVG and their departure from the airfoil surface earlier than the beginning of the separation of the turbulent boundary layer [12], [13][.

Visualization of the structure of the airflow was carried out with the help of mulberry profile models pasted on the surface (Fig. 3).



a)



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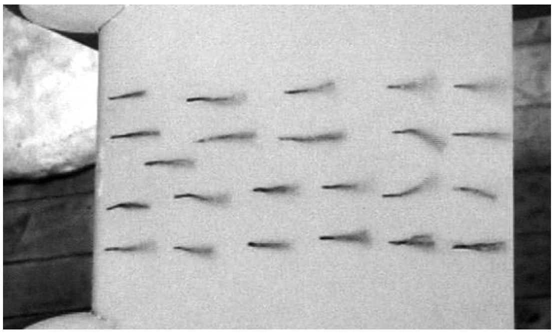

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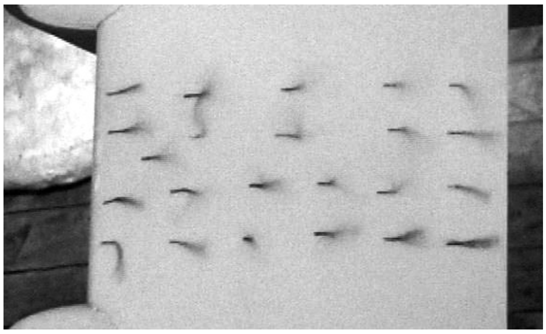

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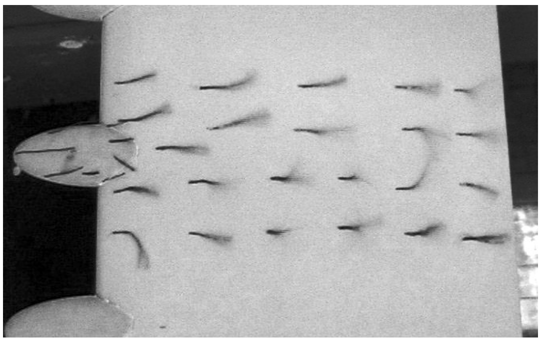

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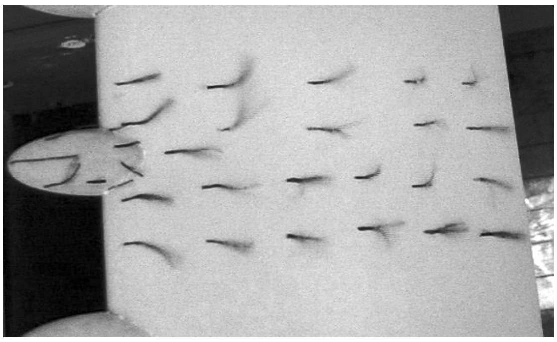

f)

Fig. 3. Visualization of airflow blowing of the aerodynamic airfoil surface without and with VVG: (a) – the angle of attack 12° with VVG; (b) – the angle of attack 12° without VVG; (c) – the angle of attack 12.5° without VVG; (d) – the angle of attack 12.6° without VVG; (e) – the angle of attack 13° with VVG; (f) – the angle of attack 23° with VVG

A pair of large vortices rotating in the plane of the surface of the profile model is formed in the region of the separation by the VVG, which creates a cross-flow.

Taking into account the new data on the three-dimensionality of vortex structures on the surface of the two-dimensional profile model under separation conditions [12], [13], the visualization results confirm the complexity of vortex structures, their interaction with the boundary layer, especially in the conditions of the creation of large longitudinal vortices from the VVG, which interact with large-scale vortices, rotating in the plane of the wing. Thus, there is an interaction of two large vortices of different types and their interaction with the turbulent boundary layer under separation conditions. Without VVG, only after the global separation, a pair of large vortices is formed in the plane of the surface near the toe of the profile. When installing the VVG, a pair of vortices is also formed at smaller angles of attack in the nose part of the profile, but the longitudinal vortex structure prevents global separation. We have a pair of vortices in the plane of the surface on the sides of the VVG, and in the wake of the VVG we have a longitudinal vortex that restrains the global separation by interacting with the boundary turbulent layer, dividing it into separate sections along the wing span by the number of installed VVG, creating an ordered vortex structure of the flow and preventing it from breaking away from the surface, introducing additional energy into the boundary layer.

IV. Conclusions

The main features of experiment in the wind tunnel aimed at researching aerodynamic airfoilmodels using volumetric vortex generators are represented. The three types of aerodynamic airfoilmodels are characterized.

The graphs show the change in the aerodynamic force coefficients in the speed coordinate system depending on the angle of attack at the different distances from the toe. In these graphs, the presence or absence of volumetric vortex generators is taken into consideration.

The visualization of airflow blowing for the aerodynamic airfoilsurface without and with volumetric vortex generators is shown.

References

[1] E. P. Udartsev, et al., *Vortex Generator. Patent on useful model*. No. 67743 from 12.03.2012.

[2] E. P. Udartsev, et al., *The generator of longitudinal vortices*. Patent on useful model. No 111701. 25.11.2016.

[3] J. S. Delinero, J. M. Di Leo, and M. E. Camocardi, "Vortex generators effect on low Reynolds number airfoils in turbulent flow," *International Journal of Aerodynamics*, 2 (1), 2020, 1: 14. https://doi.org/10.1504/IJAD.2012.046539

[4] P. S. Divekar and T. Ekbote, "Design of aerodynamic of an airplane wings," *IJSDR*, 4, 2019, 59–64. https://www.ijsdr.org/viewpaperforall.php?paper=IJSDR1910011

[5] A. G. Shcherbonos, *Aerodynamic characteristics of a wing with vortex generators in the conditions of non-stationary flow*, Dissertation of Ph.D. 2012, NAU, Kyiv. [in Ukrainian]

[6] S. I. Oleksienko, *Control of flow separation using longitudinal vortices generators*, Dissertation of Ph.D., 2018, NAU, Kyiv. [in Ukrainian]

[7] S. M. A. Aftab, N. A. Razak, A. S. Mohd Rafie, and K. A. Ahmad, "Mimicking the humpback whale: An aerodynamic perspective," *Progress in Aerospace Science*, 84, 48–69, 2016. https://doi.org/10.1016/j.paerosci.2016.03.002

[8] J. C. Lin, "Review of research on low-profile vortex generators to control boundary-layer separation," *Progress in Aerospace Sciences*, vol. 38, issues 4–5, pp. 389–420, May–July 2002. https://doi.org/10.1016/S0376-0421(02)00010-6.

[9] D. Custodio, C. W. Henoch, and H. Johari, "Aerodynamic characteristics of finite span wings with leading-edge protuberances," *AIAA Journal*, 53(7), 1878–1893, 2015. https://doi.org/10.2514/1.J053568.

[10] A. K. Malipeddi, N. Mahmoudnejad, and K. A. Hoffmann, "Numerical analysis of effects of leading-edge protuberances on aircraft wing performance," *Journal of Aircraft*, 49(5), pp. 1336–1344, 2012. https://doi.org/10.2514/1.C031670.

[11] O. A. Sushchenko and Y. N. Bezkorovainyi, "Improvement of UAV positioning by information of inertial sensors," in *Proceedings of IEEE 5th International Conference on Methods and Systems of Navigation and Motion Control (MSNMC)*, Kyiv, Ukraine, 2018, pp. 151–155. https://doi.org/10.1109/MSNMC.2018.8576307.

[12] O. Zhdanov, V. Orlianskyi, and O. Sushchenko, "Research of aerodynamic characteristics of aviation profile model in conditions of artificial generation of large longitudinal vortices," *CEUR Workshop Proceedings*, 3732, 2024, pp. 149–160.

[13] O. Zhdanov, V. Orlianskyi, and O. Sushchenko, "Researching Influence of Vortex Generators on Aircraft Aerodynamic Characteristics," *Proceedings of the 2nd International Workshop on Advances in Civil Aviation Systems Development*, [*Lecture Notes in Networks and Systems ((LNNS, vol. 992))*], pp. 410–422. https://doi.org/10.1007/978-3-031-60196-5_30

[14] O. A. Sushchenko and A. A. Tunik, "Robust stabilization of UAV observation equipment," in *Proceedings of 2nd International Conference on Actual Problems of Unmanned Air Vehicles Development*, Kyiv, Ukraine, 2013, pp. 176–180. https://doi.org/10.1109/APUAVD.2013.6705318

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Zhdanov Oleksander. ORCID 0000-0001-5273-571X. Senior Researcher.
Aerospace Faculty, National Aviation University, Kyiv, Ukraine.
Education: Kyiv Institute of Civil Aviation Engineers, Kyiv, Ukraine, (1982).
Research area: aerodynamics of aircraft.
Publications: 10.
E-mail: azhdanov@nau.edu.ua

Sushchenko Olha. ORCID 0000-0002-8837-1521. Doctor of Engineering. Professor.
Faculty of Air Navigation, Electronics and Telecommunications, National Aviation University, Kyiv, Ukraine.
Education: Kyiv Polytechnic Institute, Kyiv, Ukraine, (1980).
Research area: systems for stabilization of information-measurement devices.
Publications: 251.
E-mail: sushoa@ukr.net

Orlianskyi Valerii. ORCID 0009-0000-8186-4211. Researcher.
Aerospace Faculty, National Aviation University, Kyiv, Ukraine.
Education: Kyiv Institute of Civil Aviation Engineers, Kyiv, Ukraine, Kyiv, Ukraine, (1987).
Research area: wind tunnel experiments.
Publications: 2.
E-mail: aerodyn@nau.du.ua

О. І. Жданов, О. А. Сущенко, В. В. Орлянский. Дослідження моделі аеродинамічного профілю з вихроутворювачами в аеродинамічні трубі

У статті досліджено модель профілю крила безпілотного літального апарата в аеродинамічній трубі з використанням об'ємних вихрових генераторів. Описано об'ємні вихроутворювачі трьох типів для конкретної продувальної моделі з урахуванням її геометричних характеристик. Наведено особливості установлення об'ємних вихроутворювачів на поверхні моделі профілю. Представлено особливості експерименту в аеродинамічній трубі. Показано порівняльне змінювання аеродинамічних характеристик моделі профілю з об'ємними вихроутворювачами та без них у вигляді графічних залежностей. Порівняння проведено для різних значень чисел Рейнольдса. Проведено аналіз отриманих залежностей. Проілюстровано візуалізацію повітряного потоку експериментальним шляхом. Результати спрямовані на покращення аеродинамічних характеристик безпілотних літальних апаратів. Основне значення дослідження полягає в удосконаленні поведінки безпілотних літальних апаратів у зоні критичних кутів атаки. Отримані результати можуть бути корисними також для літаків широкого класу.

Ключові слова: профіль крила; об'ємний вихроутворювач; аеродинамічна труба; аеродинамічні характеристики; аеродинамічна якість; експеримент.

Жданов Олександр Іванович. ORCID 0000-0001-5273-571X. Старший науковий співробітник.
Аерокосмічний факультет, Національний авіаційний університет, Київ, Україна.
Освіта: Київський інститут цивільної авіації, Київ, Україна, (1982).
Напрям наукової діяльності: аеродинаміка літаків.
Кількість публікацій: 10.
E-mail: azhdanov@nau.edu.ua

Сущенко Ольга Андріївна. ORCID 0000-0002-8837-1521. Доктор технічних наук. Професор.
Факультет аеронавігації, електроніки та телекомунікацій, Національний авіаційний університет, Київ, Україна.
Освіта: Київський політехнічний інститут, Київ, Україна, (1980).
Напрям наукової діяльності: системи стабілізації інформаційно-вимірювальних пристроїв.
Кількість публікацій: 251.
E-mail: sushoa@ukr.net

Орлянський Валерій Валентинович. ORCID 0009-0000-8186-4211. Дослідник.
Аерокосмічний факультет, Національний авіаційний університет, Київ, Україна.
Освіта: Київський інститут цивільної авіації, Київ, Україна, (1987).
Напрям наукової діяльності: випробування в аеродинамічній трубі.
Кількість публікацій: 2.
E-mail: aerodyn@nau.du.ua