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UASAGE OF ARTIFICIAL VORTICES FOR RESEARCH OF AERODYNAMIC CHARACTERISTICS OF AIRCRAFT

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Abstract—*This article solves the problem of widening the range of the angle of the attack of safe flight using volumetric vortex generators. The research method is based on experimental tests in the wind tunnel. Analyzing the obtained results allows us to research changes in the integrated aerodynamic characteristics. The features of the experimental test are described. The volumetric vortex generators of three types for the definite blowing model are represented. A comparative analysis of the aerodynamic characteristics of the profile model in the form of graphical dependencies is represented. The graphs show the change in the aerodynamic force coefficients in the speed coordinate system. The visualization of airflow was carried out. Volume vortex generators are described. A description of the experiment in the wind tunnel is given. The analysis of the obtained results has been carried out. Layouts of profile models with lateral screens are represented. The obtained results can be useful for aircraft of a wide class especially for unmanned aerial vehicles. The results can be used in synthesis control laws in disturbed stabilization and control systems.*

Index Terms—Vortices; wind tunnel; aerodynamic characteristics; aerodynamic profile model; experiment.

I. INTRODUCTION AND PROBLEM STATEMENT

The problem of widening the range of changing attack angles for the safe operation of unmanned aerial vehicles (UAVs) is relevant in scientific areas and practical applications. It can be solved by installing volumetric vortex generators (VVG) on the wing front edge and optimizing the geometric parameters of their shape and location.

This article studies the possibility and efficiency of using an artificially organized system of big longitudinal vortexes. The emphasis has been placed on modifying space-time scales and developing a practical approach to creating 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 lies in experimental weight tests of the profile model in the wind tunnel and comparative analysis of their results in the form of changes in integral aerodynamic characteristics.

There are vortex generators (VG) with different shapes and dimensions. Prototypes of VG could be characterized by various geometrical characteristics such as the chord, area, volume, setting angle, and installation step.

Forming a shape of VG, it is desirable to achieve the maximal efficiency of the longitudinal vortex. For this, the longitudinal vortex must be mounted on the profile model surface in correspondence with some requirements. It means that power consumption of the external air flow must be minimized. Moreover, the length of the vortex along the profile chord must be minimized also. It is necessary to eliminate the longitudinal vortex backward in conditions of changing the pressure gradient on the profile surface.

The vortex source can be located at the point, which is contacting with the VVG and aerodynamic surface simultaneously. Is noteworthy that the interference phenomenon can create positive or negative conditions because it can create a decrease or increase in front drag force. It is necessary to remember that the VG itself can be a source of the vortex. As an example, we can consider components of the VG arising outside the profile model and arranged at some angle relative to the airflow. Some valleys and ledges of the VG surface also can be sources of vortexes. Hence, we deal with the possible negative consequences of interference. To decrease these negative consequences and even to improve the situation, we must ensure smooth transitions between the profile model and VG [3], [4].

The efficiency of generating vortexes depends on the attack angle. The influence of VG must be minimal in cruising modes. And especially the possibility of arising critical attack angles has a great significance. Therefore, we must locate the VG relative to a chord in a definite way considering the chord curvature. It is possible also to improve this situation by varying the angular location of VG depending on the airflow conditions [5]. It is desirable to increase the suction force both on the surface of the airfoil and the toe of the profile model. This can be done by forming the shape curvature of the airfoil surface shape. This influences the airflow acceleration in the boundary layer on the surface of the airfoil and profile model toes [6].

The number of factors that influence characteristics of aerodynamic surface compositions with VVG, based on the results of research studies [7], [8] include the following factors. They include the external shape of the VG, profile model dimensions, the arrangement by the size of the peak far off the profile frontal edge, the inclination angle of the chord of the VG relative to the chord of the profile, the step of setting the VG according to the scale of the model, and others. Carrying out such multifactorial studies to determine optimal layouts requires a large number of tests of layout models, analysis of results, and determination of optimal layouts according to chosen criteria [9], [10].

II. Description of Experiment

The experiments were carried out in a closed-type low-velocity aerodynamic atmospheric tube with an open working part of an elliptical cross-section with the dimensions of the axes 750x420 mm and a length of 900 mm. The airflow speed was 3.5 ... 30 m/s. The air tube is equipped with an external three-component rider aerodynamic weight, which provides the measurement of three components of the total aerodynamic force. The measured forces allow us to calculate the dependence of dimensionless aerodynamic coefficients on the attack angle. The built-in device for setting the angle location of the profile model provides changing attack angles in the range $\alpha = -20° ... +40°$.

The model suspended in the wind tunnel must have the possibility of circular blowing at the angle of attack in separate areas within the available range of changing the angular location. The mechanical system for decomposing the forces of the rider weight can be connected to the system of tensor converters of loads on weight components into electrical signals. The set of strain gauges provides automation of the process of measurement and recording of test results. It should be pointed out that tests are accompanied by changing the angular position of the profile model. Measurement results are displayed in the form of dependences of aerodynamic coefficients on the angle of attack.

As the studied model of the aerodynamic surface, the compartment model of the classical symmetrical NACA0012 profile was initially chosen. Such a model is often applied in tests. This blowing model is characterized by a rectangular form. The model's characteristics are as follows: the span – 350.0 mm, the chord – 175.0 mm, the area – 0.06125 m^2, and the geometric prolonging – $\lambda = 2$. The longitudinal model's axis is arranged at an interval of 25% of the chord length or 0.04375 m relative to the toe. It is observed that the angle location is determined relative to the longitudinal axis. Vertical shields are mounted on the specific side profile model. The chosen sides must ensure a maximally effective expansion 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. First of all, it concerns 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 consists of VVG models. Volumetric vortex generators are arranged in the toe of the profile model. which are installed in the toe part. Using the technical information about the different types of VG, turbulators, aerodynamic influxes, and other means of controlling vortex structures [11] – [13], the basic forms of VVG were created.

The selected types of VVG generate longitudinal vortices of different intensities and with different spatiotemporal characteristics. In addition to the shape of the VVG, the factors influencing the characteristics of the generation of the system of longitudinal vortexes are the size of the VVG, their number, and the geometric characteristics of the mounting place.

The chosen forms of VVG generate longitudinal vortices of different intensities and with various spatial and temporal characteristics [10] – [12].

The dimensions of the VVG installed on the aerodynamic aerofoil 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, [14]. 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 aerofoil 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 influence of the mounted VVG on the aerodynamic characteristics of the NACA0012 profile model was implemented based on a comparative analysis of the dependences of the aerodynamic coefficients as a function of the attack angle. These dependencies were plotted on the same graph both for a pure profile and a profile with mounted VG. The dependences of the aerodynamic coefficients describe the changing of total loadings. Nevertheless, they are quite informative to show the differences in the behavior of the dependencies. They also allow us to propose assumptions relative to the change in the structure of the flowing upper surface of the model while achieving critical attack angles and flow separation. The aerodynamic dependences for the layout of the first type VVG are compared in Figs 1 and 2. Model in the amount of 5 pieces and the size of 20% are mounted with a step of 70 mm. The graphs allow us to analyze the main specific effects of the mounted VVG on the aerodynamic characteristics of the profile model. During the tests, the comparison was made for three values of the Reynolds numbers. The graphs make it possible to make the main observations about the efficiency of the mounted VVG on the separation properties, 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 influence of the Reynolds number on the change in the aerodynamic characteristics of the model in the region around the critical and the critical attack angles due to the installation of the VVG.

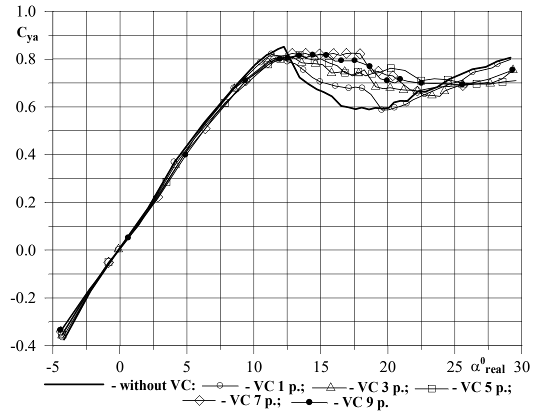

Fig. 1. The influence of quantity and step of VG of the first type for the relative size of the chord 7.5% and setting angle $\gamma = 0$ on the plot $c_y = f(a)$ of the profile model NACA0012 in conditions of airflow speed $V = 18.0$ m/s (Reynolds number Re ≈ 200000)

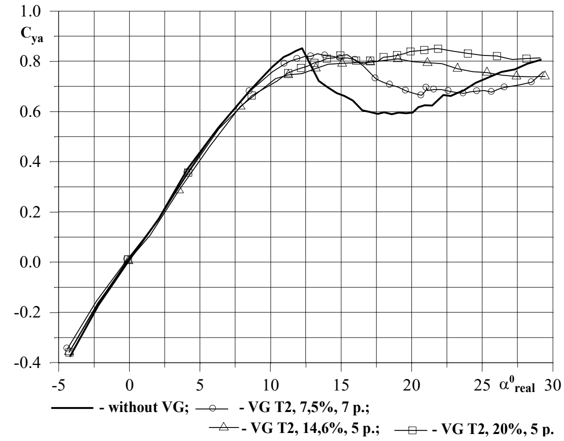

Fig. 2. The influence of quantity and step of VG of the second type of the relative size of the chord 7.5% and setting angle $\gamma = 0$ on the plot $c_y = f(a)$ of the profile model NACA0012 under conditions of airflow speed $V = 18.0$ m/s (Reynolds number Re ≈ 200000)

This is the additional turbulence of the flow on the surface of the model from the turbulators. Installation of turbulators actually eliminates the characteristic change in aerodynamic characteristics during flow stalling.

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. This indicates the stability of the airflow structure, realized by the imposition of a system of large longitudinal vortices on the airflow structure of a pure profile at the critical angles of attack.

It is known that a drastic decrease in the lifting force after reaching the critical angle of attack is caused by a global separation of the airflow on the upper surface of the profile model. Initially, the separation of the turbulent boundary layer develops gradually with an increase in the attack angle. The separation line moves from the trailing edge of the profile toward the flow. This process is reflected in the plot of the dependence $c_{ya} = f(a)$ in the appearance of changing non-linearity. There is a jump-like transition of the separation line to the toe of the profile at some point when the separation line approaches the line of maximum profile thickness. Such a process is called global separation. It has a divergent uncontrolled nature and spreads over the entire upper surface of the profile model. As a result, there are sharp changes in the behavior of the aerodynamic characteristics dependencies $c_{ya} = f(a)$, $c_{xa} = f(a)$ for the pure profile model. They are especially noticeable in the behavior of the most sensitive characteristic $m_{z1} = f(a)$.

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 values of attack angles in the conditions of the use of VVG are observed. Turbulent separation in the presence of VVG begins at smaller angles of attack as follows from the earlier appearance of a characteristic nonlinearity in the behavior of the dependence c_{xa}. Most likely, this is caused by increased turbulence of the boundary layer by longitudinal vortices from the VVG. Also, the separation of vortices from the airfoil surface occurred earlier than the beginning of the separation of the turbulent boundary layer.

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 [18] we can make the following conclusions. The visualization results confirm the complexity of vortex structures interacting with the boundary layer, especially in the conditions of the creation of large longitudinal vortices from the VVG. They 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, a pair of large vortices is formed in the plane of the surface near the toe of the profile only after the global separation.

When installing the VVG, a pair of vortices is also formed at smaller angles of attack in the toe part of the profile. Nevertheless, 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 a longitudinal vortex in the track of the VVG. The longitudinal vortex restrains the global separation by interacting with the boundary turbulent layer. This is implemented by dividing 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.

Due to the installation of vortex generators, is possible to predict an increase in the critical value of the attack angle and the maximal lifting force and improve the flight-technical characteristics. Such correction of the aerodynamic characteristics of the carrying surface is important in the event of unpredictable near-critical and over-critical angles of attack, regardless of the factor that caused the violation of the limits of the permissible area of operation. These factors can include the influence of atmospheric phenomena, piloting errors, or something else. On the other hand, the installation of vortex generators should not impair the characteristics of the flight cruising mode. It is desirable to keep values of the maximum aerodynamic quality and the most favorable angle of attack. From this point of view, the criteria for the optimality of the layout of the profile model with the volumetric VG can be the behavior of the lifting force on the near-critical and over-critical attack angles. On the contrary, the absence of the VG can be characterized by the values of the critical attack angle, the maximum value of the coefficient of the lifting force, the gradient in the supercritical area, and the angle of attack from which the violation of linear dependence begins. Important criteria will be the magnitude of the change in aerodynamic quality in cruising flight modes due to the installation of the VG, the magnitude of the most advantageous angle of attack, and features in the change in the dependence of the longitudinal moment on the angle of attack.

The effect of the installation of the VG on the airflow around the bearing surface lies in the artificial creation of an ordered system of large longitudinal vortexes by the span of the model. It interacts with the external airflow and ensures a gradual and smooth local restructuring of the airflow structure on the upper surface of the profile while approaching the over-critical attack angles. In contrast to the conditions of the absence of vortex generators, this process is global and occurs explosively. The consequence of installing vortex generators should be an increase in the critical angle of attack and the absence of a drastic drop in the lifting force in the critical region. To increase the lifting force, it is necessary to shape the upper surface of the toe part of the vortex generator in such a way (for example, to set a certain curvature and increase the local speed) that a suction force arises in this place. In the speed coordinate system, the projections of this force increase the lifting force and decrease the drag [22] – [24].

The effectiveness of the application of the VG is influenced by its size relative to the dimensions of the profile, the number, and the step of their installation along the span of the profile model, which together determines the surface area of the air conditioner served by the air conditioner. The angle of installation of the vortex generator relative to the airfoil chord affects the change of the aerodynamic characteristics of the airfoil model by the angle of attack.

As we can see, there are several geometrical parameters regarding the dimensions of the VG of a certain type and their location, which affect the aerodynamic characteristics of the profile models, and we have six profile models. There are also some criteria for the efficiency of using vortex generators. Therefore, to find out the influence of the above factors, a multivariate experiment with a large number of trials should be carried out.

To shorten the test program, it was decided to determine the geometric characteristics of the effective arrangement of the VG of 3 types of the developed shape for the model of one type of aerodynamic profile and to carry out further studies of the layouts of other profiles only for the determined effective arrangement of the selected profile. We define such a layout as quasi-optimal of a local nature because in general, more efficient layouts are also possible according to other criteria of optimality. The NACA0012 symmetrical profile, well-known in experimental aerodynamics, was chosen as such profile. Layouts of profile models with lateral screens are represented in Fig. 3.

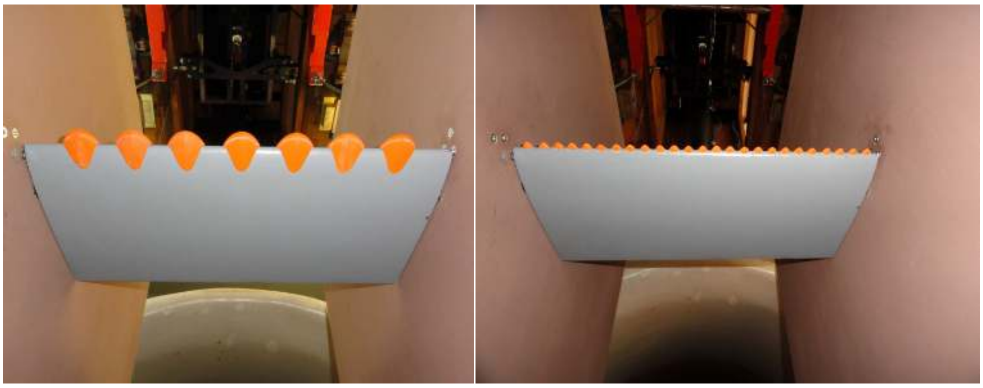

Fig. 3. Layouts of profile model with lateral screens

The carried out research can be useful for synthesis control laws in disturbed stabilization and control systems [25] – [27] and reliable navigation measurements [28] – [30].

IV. CONCLUSIONS

The expected results of research in wind tunnels consist of improving the interaction of VG with the features of the dynamics of the flow around the wing, the distribution of velocity and the change in the pressure gradient along the wing, and the interaction of eddy currents on the wing with terminal vortices. The results of experimental studies will make it possible to set the problem of forming a class of profiles of vortex active wings.

The most effective arrangement for each of the 3 types of the form of the VU turned out to be their installation with a step of 70 mm (20% of the span of the model) in the amount of 5 pieces with an angular position γ = 0. The magnitude of the VU protrusion beyond the front edge of the profile is 20% of the chord length of the profile.

The graphs show the change in the aerodynamic force coefficients in the speed coordinate system, the longitudinal moment coefficient relative to the point on the profile chord at a distance of 25% from the toe, and the aerodynamic quality graph.

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О. І. Жданов, О. А. Сущенко, В. В. Орлянский. Використання штучних вихорів для досліджень аеродинамічних характеристик літаків

У статті вирішено задачу розширення діапазону кута атаки безпечного польоту за допомогою об'ємних вихрогенераторів. Метод дослідження заснований на експериментальних випробуваннях в аеродинамічній трубі. Аналіз отриманих результатів дозволяє досліджувати зміни інтегральних аеродинамічних характеристик. Описано особливості експериментальної перевірки. Представлені об'ємні вихрогенератори трьох типів для певної моделі видування. Наведено порівняльний аналіз аеродинамічних характеристик моделі профілю у вигляді графічних залежностей. На графіках показано зміну коефіцієнтів аеродинамічних сил у системі координат швидкості. Проведено візуалізацію повітряного потоку. Описано об'ємні вихрові генератори. Дано опис експерименту в аеродинамічній трубі. Проведено аналіз отриманих результатів. Представлені компонування профільних моделей з бічними екранами. Отримані результати можуть бути корисними для літаків широкого класу, особливо для безпілотних літальних апаратів. Результати можуть бути використані в синтезі законів керування в збурених системах стабілізації та керування.

Ключові слова: вихори; аеродинамічна труба; аеродинамічні характеристики; модель аеродинамічного профілю; експеримент.

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