UDC 681.5.015(045)

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FEATURES OF AUTOMATIC FLIGHT CONTROL SYSTEM OF UAV WITH VORTEX-ACTIVE WING

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Abstract—*Improvement of unmanned aerial vehicle navigation reliability in rough air and gusts is provided by aerodynamic characteristics of unmanned aerial vehicle. Investigation of leading edge vortex generators effectiveness in subsonic wind tunnels and on RC airplane was presented. Aerodynamic features of UAVs with vortex-active wing, which should be considered during the development of automatic flight control system, were considered.*

Index Terms—Vortex-active wing; vortex generator; aerodynamic investigation; flight test; unsteady characteristics; automatic flight control system.

I. The Purpose of Research

The purpose of research is to improve UAV navigation quality in rough air. Significant increase of stall angle allows piloting UAV in the second flight mode with improved stability and control characteristics and enhances safety of flight in vertical gusts.

Research hypothesis is that the longitudinal vortex produced by the leading-edge vortex generators reaches the trailing edge of the wing. It results in reorganization of flow over wing pattern and different aerodynamic characteristics at high angles of attack. Group of developed in that way lifting surfaces is called “Vortex-active wing” [1]. It can be used both on wings of different types of aircraft including UAV, control surfaces, and stabilizer.

Automatic flight control system (AFCS) of UAVs with vortex-active wing must meet basic aerodynamic requirements. Problem of aerodynamic model of vortex-active wing and AFCS integrating was set.

II. Problem and Practical Tasks

Safety flight in rough air achieves by potential to overcome gust without reaching stall angle of attack. The main objective of aerodynamics in this case consists in developing methods to increase critical angles of attack, leading to an increase in the allowable flight angles of attack. One of the known methods of increasing the critical angles of attack is to use turbulators on wing and tail [2]. Turbulators influence on the flow in the boundary layer, mixing it on substantial distance behind the turbulators, and effectively delay the separation caused by viscosity, reducing the influence of the pressure gradient on airflow. The turbulators effect depends on velocity profile in the boundary layer, the intensity of mixing flow and location of vortex structures in stall. To solve the problem of vortex flow over the wing control is necessary to study characteristics of unsteady vortex flow over the wing, such as problem of dynamic flow separation that occurs on the wing in supercritical region of angles of attack. Article [3], published in proceedings of 2013 IEEE conference, analyses the dynamics of the vortex motion while increasing an angle of attack. These results show that it is necessary to influence on dynamic vortex, which originates on the upper surface near the leading edge, to control flow separation. Evolution of dynamic vortex downstream leads to interference with the viscous separation vortex near the trailing edge of the wing. Dynamics of vortex interaction determines the aerodynamic characteristics of the wing.

Analysis of the results of [3] reveals that it is necessary to oppose to vortex structures near the leading edge and the trailing edge of an airfoil. This requires that the impact on the flow over the wing had enough energy to reach the trailing edge of the wing. Since the turbulator energy is small, they are basically mounted in front of viscous separation zone near the trailing edge of the wing. To influence the flow along the wing chord, powerful carriers of energy than turbulized flow in the boundary layer are necessary. Vortex flow along the wing chord that is perpendicular to the separation vortexes can provide it.

Lift coefficient dependence on time while an angle of attack reaches critical angle of attack, which is equal to 18 degrees, and further development of vortices up to an angle of attack 30 degrees was studied. Lift coefficient reaches maximum value, attached vortex appears at the leading edge of the wing. At 30 degrees vortex detaches and becomes large therefore lift coefficient steeply falls to minimum. At that moment pattern of interaction of leading edge vortex that has detached and trailing edge viscous separation vortex reveals. Vortexes move away from the airfoil causing increase of lift coefficient. Lift coefficient increases with vortex moving away. Then unsteady flow around wing at 30 degrees reiterates.

The fact is that separation wingspan vortexes (transversal vortex) react on fluctuations. These fluctuations can be produced by longitudinal vortex generators (LVG), which are mounted on the leading edge of the wing. Longitudinal vortexes, appeared at the leading edge of the wing, are effective energy carriers. Article [4] reveals that longitudinal vortex, produced by leading edge extension, reaches the trailing edge, while velocity on the surface of the wing can grow up to 1.5 times. Leading edge root extension effect is widely used on the low aspect ratio wings of modern fighters [5].

To solve the problem of increasing the critical angle of attack of the wing, it is necessary to realize the hypothesis that vortex, which appeared at the leading edge, has enough intensity to continue stable motion in gradient airflow up to explosion at the trailing edge. Few longitudinal bundles that situated with some wingspan interval deactivate transversal vortexes, leading to critical angle of attack and lift increase.

Figure1 represents vortex slat that successfully passed flight tests.

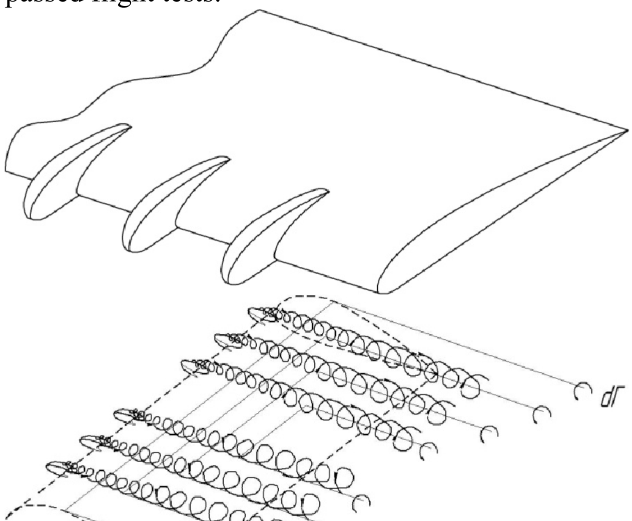

Fig. 1. Vortex slat and its vortex system

III THE RESULTS OF LVG EXPERIMENTAL STUDIES

Research of different types of LVG was carried out in small subsonic tunnel on rectangular wing (400×150×25) with airfoil relative thickness of 17 %, turbulence intensity of 2 %, Reynolds number of 2×10^5.

Influence of different types of longitudinal vortex generators and one turbulators type at the aerodynamic characteristics of wing at the angle of attack up to 33 degrees was investigated in the UTAD-2 wind tunnel.

We mounted longitudinal vortex generators on the leading edge of the wing with an interval of 50 mm.

Shapes of tested LVG and turbulators are shown in Fig. 2.

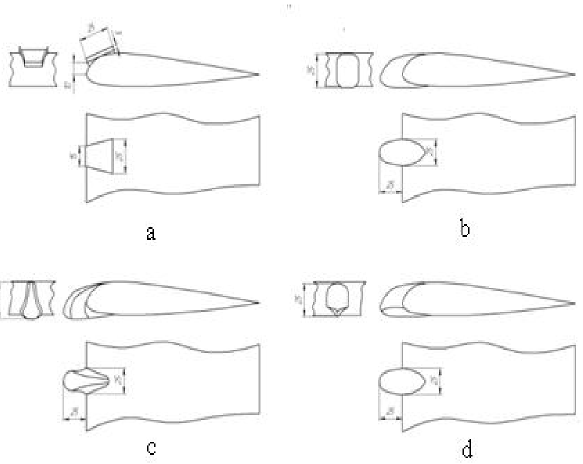

Fig. 2. Longitudinal vortex generators types: a) trapezoidal turbulators; b) 1st modification; c) 2nd modification; d) 3rd modification

Experiment results LVG are shown in Figs 3–5.

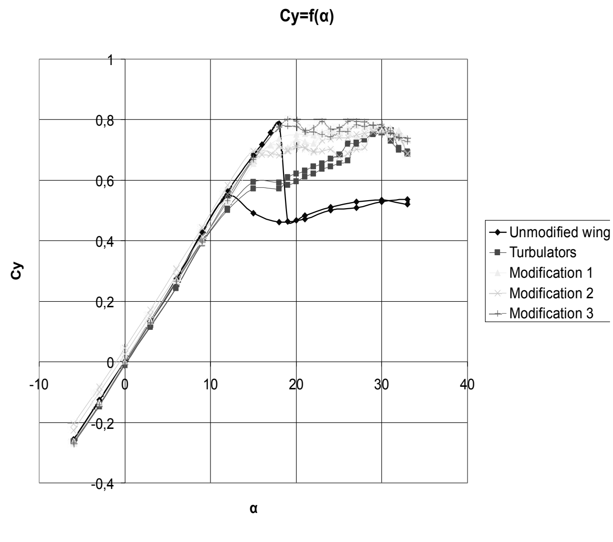

Fig. 3. $c_y = f(\alpha)$, lift coefficient graph

Unmodified wing has the clearly defined hysteresis at critical angles of attack. LVG eliminate static hysteresis on the lift curve. LVG slightly increase drag at flight angles of attack.

Turbulators reduce aerodynamic quality. Some LVG have almost no impact on drag coefficient due to suction force.

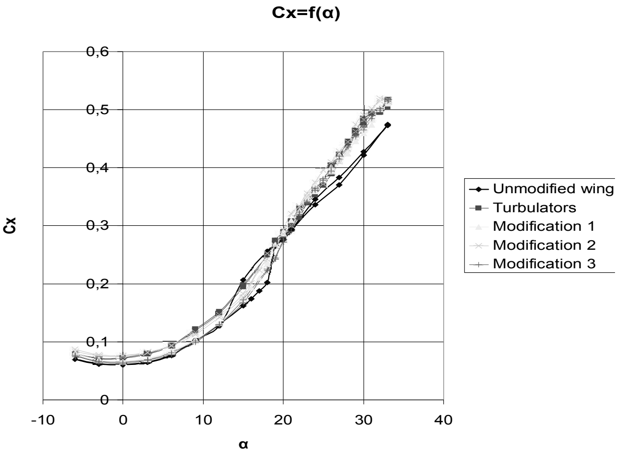

Fig. 4. $c_x = f(\alpha)$, drag coefficient graph

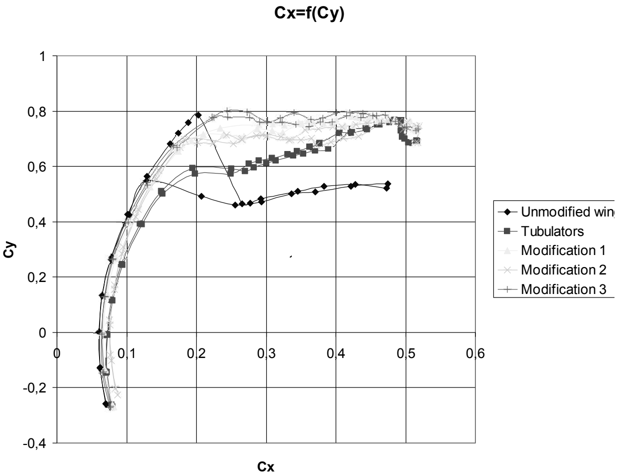

Fig. 5. $c_y = f(c_x)$, lift-to-drag graph

IV. Aircraft Scale Models Investigation

The scale aircraft model of Aeroprakt A-20 [6] with LVG on the leading edge was tested in TAD-2 wind tunnel. Wingspan of aircraft scale models was 1.1 m, free stream velocity of 40 m/s, Reynolds number of 3×10^6 at airfoil chord of 262.6 mm.

Aeroprakt A-20 model with symmetric leading-edge vortex generators in wind tunnel is shown in Figs 6–10.

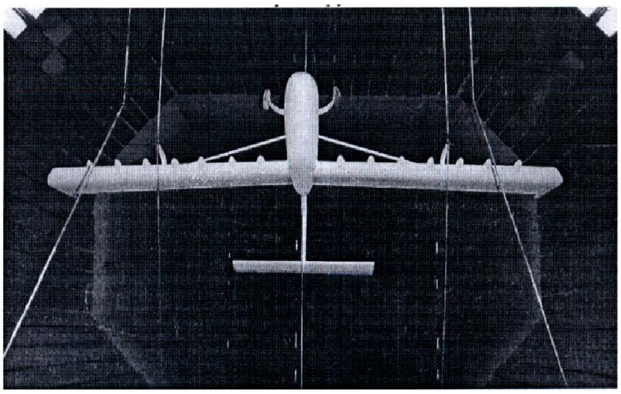

Fig. 6. Aeroprakt A-20model in TAD-2 wind tunnel

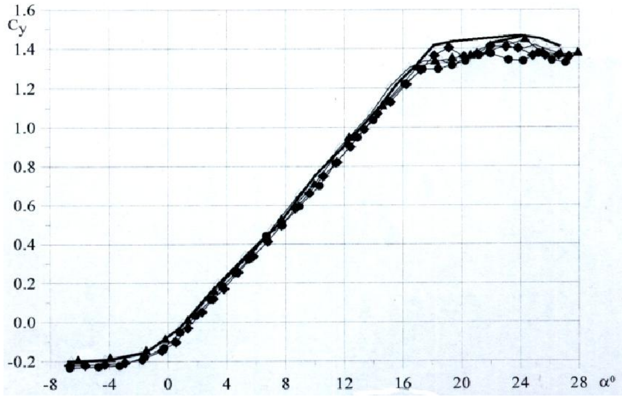

Fig. 7. $c_y = f(\alpha)$, lift coefficient graph

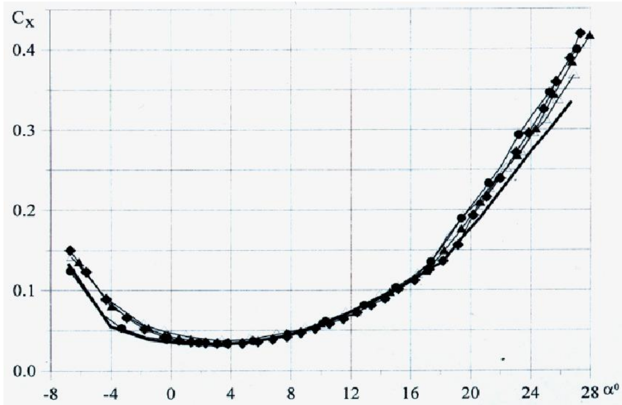

Fig. 8. $c_x = f(\alpha)$, drag coefficient graph

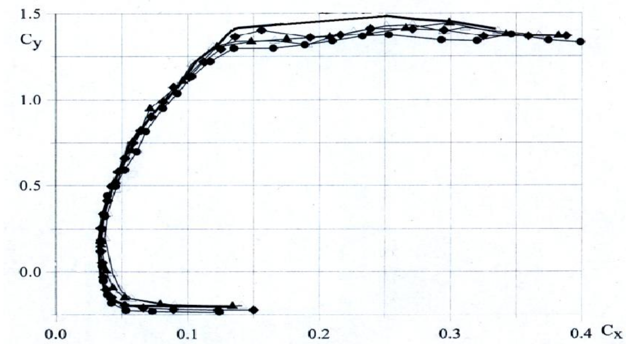

Fig. 9. $c_y = f(c_x)$, polar graph

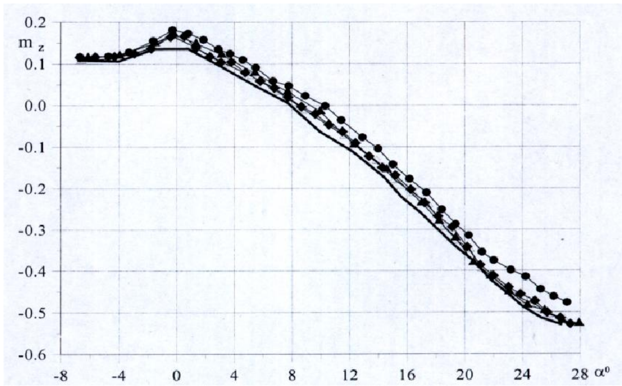

Fig. 10. $m_z = f(\alpha)$, momentum coefficient graph

Vortex generators of Aeropract A-20 are not optimized

V. Features of Automatic Flight Control System of UAVs with Vortex-active Wing

Parameters of automatic flight control system (AFCS) must take into account typical features of vortex-active wings:

– UAVs with vortex-active wing have wide flight envelope at the second flight mode;

– critical angle of attack value increases from 18-20º to 28-30º (see Fig. 3);

– lift of vortex-active wing is significantly bigger, comparing to unmodified wing at;

– lift-to-drag ratio at high angles of attack is bigger comparing to common wings (see Fig. 5). Moreover, at subsonic speed profit in lift-to-drag ratio non-linearly depends on aircraft static stability ($m_z^{Cy} \prec 0$). At the low lift coefficients (C_y) optimum is reached near neutral stability ($m_z^{Cy} = 0$). At high C_y ΔK optimum shifts to bigger instability zone ($m_z^{Cy} \succ 0$). As value increases, profit in lift-to-drag ratio increases with increase of aerodynamic negative stability of the aircraft [7]. Automatic flight control system must provide flight of statically unstable aircraft and also set thrust variation in the form of double thrust at second flight modes;

– value of aerodynamic balancing drag has considerable importance for optimal piloting. Algorithm of balancing drag analysis can be based on formula that considers drag dependence on static stability.

$$c_{x\text{bal}} = c_{x\text{a}}(c_{y\text{a}})_{\varphi=0} + \frac{m_z^{C_y}}{\bar{L}_{Г.О.}} \frac{1}{c_{\text{уп}}^{\varphi}} \left[\frac{m_z^{C_y}}{\bar{L}_{Г.О.}} + 2\frac{c_{\text{уп}}^{\varphi}}{c_{\text{уп}}^{\alpha}}(1-\alpha\varepsilon^{\alpha})(1-\frac{m_z^{C_y}}{\bar{L}_{Г.О.}}) \right] \times c_{y\text{bal}}^2 \left[1 + 0{,}4((1-\frac{m_z^{C_y}}{\bar{L}_{Г.О.}})c_{y\text{bal}})^4 \right],$$

where $c_{y\text{bal}}$ and $c_{x\text{bal}}$ are balancing coefficients of lift and drag of an aircraft; $c_{xa}(c_{ya})_{\varphi=0}$ is the lift-to-drag function of aircraft at $\varphi = 0$, where c_{ya} depends on $c_{y\text{bal}}$ by equation $c_{y\,\text{a}} = (1 - m_z^{C_y} / \bar{L}_{Г.О.}) c_{y\,\text{bal}}$; a is the coefficient that characterize degree of suction force realization at an aircraft horizontal stabilizer ($a \approx 0{,}5$).

Flight parameters can be optimized by means of balancing drag polar.

– Automatic flight control system must provide stability in flight with gusts. Margin to permissible angle of attack for UAVs with vortex-active wing can be obtained by means of formula:

$$\alpha = \alpha_{\text{opt}} + \frac{W}{V} 57{,}7°.$$

– Automatic flight control system must provide decrease of airframe stress under gusts conditions.

– Automatic flight control system of UAVs must take into account unsteady flight conditions.

Dynamic characteristics of UAVs with vortex-active wing were studied in dissertation [7]. Mathematical model of aerodynamic coefficient variation was investigated:

$$c_y = c_{y0} + c_y^{\alpha} \cdot \alpha + c_y^{\dot{\alpha}} \cdot \dot{\alpha} + c_y^{\ddot{\alpha}} \cdot \ddot{\alpha}.$$

Modelling was conducted with Strouhal number $St = \frac{b_a \chi}{V}$ (χ is- oscillations frequency) of 0-0,2 and Reynolds numbers of $0{,}7 \cdot 10^6$-$11 \cdot 10^6$. Excample of lift coefficient dependence on frequency for harmonic oscillations with amplitude of $5°$ is in Fig. 11.

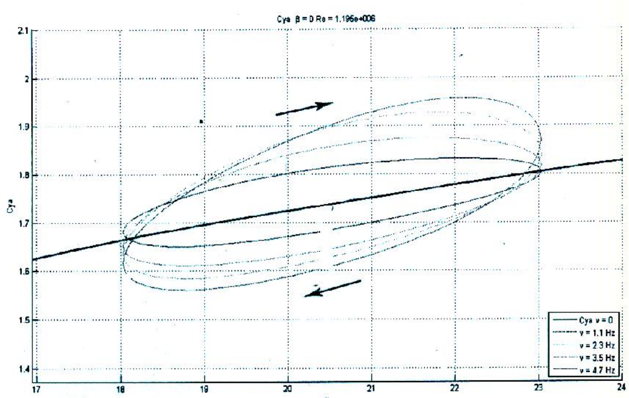

Fig. 11. $c_y = f(\alpha)$ for wing oscillations

Derivative of aerodynamic coefficient $c_y^{\dot{\alpha}}$ virtually does not depend on Reynolds number, however it vitiates with Strouhal number. For example, $c_y^{\dot{\alpha}} = -0{,}6$ at $St = 0{,}02$, , $c_y^{\dot{\alpha}} = 0{,}2$ at $St = 0{,}15$.

Derivative of aerodynamic coefficient $c_y^{\ddot{\alpha}}$, as well as $c_x^{\dot{\alpha}}$, $m_z^{\dot{\alpha}}$, $m_z^{\ddot{\alpha}}$, considerably depends on Reynolds number.

Automatic flight control system that takes into account unsteady flight conditions of UAVs has to be developed after detailed investigation of aircraft dynamic characteristics in flight tests.

Balance of UAVs in lateral motion in gusts conditions is of particular interest. Effectiveness of control depends on aerodynamic characteristics of flight control surfaces: ailerons, flaperons and rudders.

As experiments revealed, utilization of vortex generators increases ailerons effectiveness $m_x = f(\alpha)$ at angles of attack of 18 º-24º (Fig. 12).

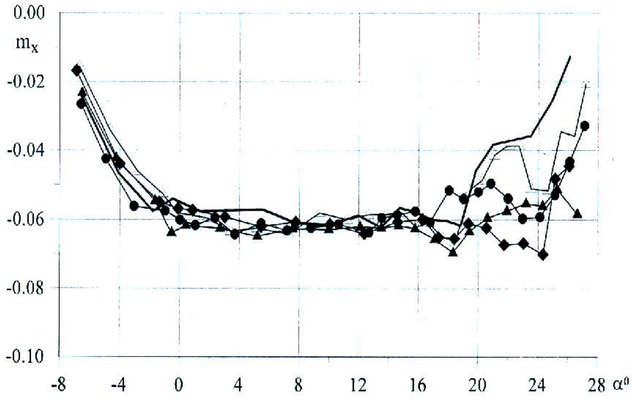

Fig. 12. $m_x = f(\alpha)$, characteristic of ailerons effectiveness

Stability about vertical axis depends on rudder effectiveness. Value of $C_{z\max} = f(\beta)$ for vortex-active fin increase from 21º to 45º (Fig. 13). It allows overcoming gusts.

Thus integration of aerodynamic characteristics of UAVs with AFCS can improve flight safety during landing, take-off and in rough air.

Furthermore, vortex generators can be mechanized, changing its angle of attack or extending out. It increases wing area, shifts aerodynamic center, increases suction force on the leading edge, decreasing aerodynamic drag, impacts on static stability. To sum it up, it is a new type of wing mechanism for aerodynamic characteristics control.

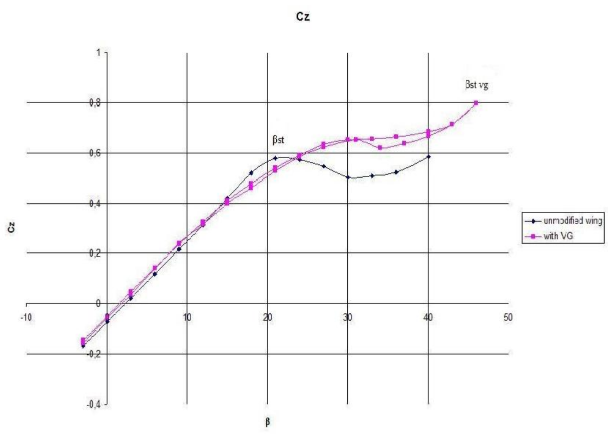

Fig. 13. $C_{z\max} = f(\beta)$, characteristic of rudder effectiveness

Performance capabilities are significantly improved in case of integration of aerodynamic characteristics of UAVs and automatic flight control system. Example of exclusive UAV configuration with vortex-active lifting surfaces is represented in Fig. 14. Configuration is based on hybrid control of UAV by means of canard and common tail. All lifting surfaces have vortex generators of the most effective shape.

Fig. 14. Computer model of UAV with vortex-active lifting surfaces

VI. FLIGHT TEST

We used RC airplane Wild duck for flight test to realize LVG effects on practice. Airplane has 1000 mm wingspan, 200 mm chord, and 2.5 cubic centimetres engine.

The first flight was on 03/12/2013. Airplane had five asymmetric leading-edge vortex generators on each outboard section of wing, which formed vortex slat (Fig. 15) [8].

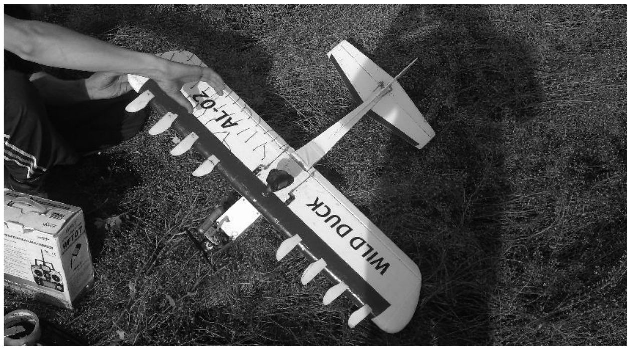

Fig. 15. The flight was recorded from the ground

The next step was recording video of visualized flow over wing of tested airplane with LVG. Visualization was provided by thread glued to the right outboard section of wing. Optimization of flow over the wing was carried out heretofore in wind tunnel UTAD-2 (Fig. 16).

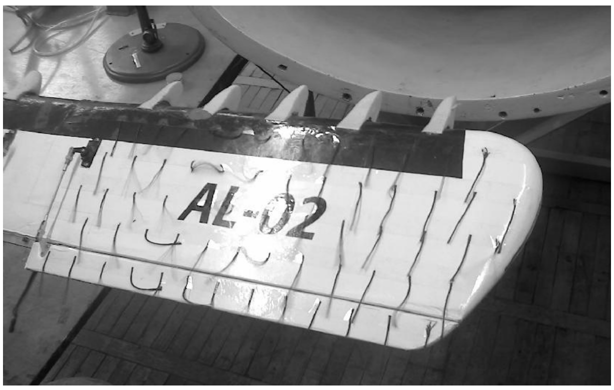

Fig. 16. Flow over wing visualization in wind tunnel

Angle of attack was changing up to visual stall to find the critical angle of attack of the wing. Then LVG were mounted on the wing with optimum interval and angle relative to chord in order to provide attached flow.

Airplane was stable and controllable in all flight regimes. Level flight, flight at critical angle of attack, aerobatic manoeuvres, and flight with turned off engine were performed. At this time, there was an appreciable 4-6 m/s wind, which did not influence on controllability.

SUMMARY

Possibility of navigation quality improvement in the second flight mode at high angles of attack was proved by means of installation of vortex generators on the leading edge that increase critical angle of attack by more than 30 degrees.

Leading edge vortex generators improve stability and control and enhance stall protection during flight in rough air and gust.

Investigation of UAV and wing model in wind tunnel revealed features of different types LVG influence at flow around airfoil.

UAVs with vortex-active wing have aerodynamic characteristics, which broaden operation range and control effectiveness of in rough air, gusts conditions and second flight modes.

Features of UAVs with vortex-active wing at second flight modes require engines control in the form of double thrust and also ensuring flight with minimal static stability or its absence.

Dynamic characteristics of aircraft with vortex-active wing, obtained in wind tunnels, reveal that dynamic loops of aerodynamic characteristics are more complete comparing to unmodified wing. Its influence on flight dynamics have to be considered in detail in flight tests in order to formulate problem statement for development of complete automatic flight control system.

Flight tests of RC airplane confirmed vortex slat effectiveness in different flight modes.

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Received 04 October 2014.

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Є. П. Ударцев, С. І. Алексєєнко., А.І. Саттаров. Особливості системи автоматичного керування БПЛА з вихреактивним крилом

Покращення надійності навігації безпілотного літального апарату у збуреній атмосфері та при поривах вітру, забезпечується за допомогою аеродинамічних характеристик безпілотного літального апарату. Представлено вивчення ефективності генераторів вихорів на передній кромці в дозвукових аеродинамічних трубах. Розглянуто аеродинамічні особливості БПЛА з вихроактивним крилом, котрі необхідно враховувати при розробці системи автоматичного управління.

Ключові слова: вихроактивне крило; вихроутворювачі; аеродинамічне дослідження; льотні випробування; нестаціонарні характеристики; система автоматичного керування.

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Е. П. Ударцев, С. И. Алексеенко., А. И. Саттаров Особенности системы автоматического управления БПЛА с вихреактивным крылом

Улучшение надежности навигации беспилотного летательного аппарата в возмущенной атмосфере и при порывах ветра обеспечивается с помощью аэродинамических характеристик беспилотного летательного аппарата. Представлено изучение эффективности генераторов вихрей на передней кромке в дозвуковых аэродинамических трубах. Рассмотрено аэродинамические особенности БПЛА с вихреактивным крылом, которые необходимо учитывать при разработке системы автоматического управления.

Ключевые слова: вихреактивное крыло; вихреобразователи; аэродинамическое исследование; летные испытания; нестационарные характеристики; система автоматического управления.

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