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UNSTEADY AERODYNAMICS OF VORTEX ACTIVE WING OF UAV AT HIGH AND SUPERCRITICAL ANGLES OF ATTACK

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Abstract**—***The concept is that the flow around the wing is formed as unsteady longitudinal vortex flow. Shape of leading and trailing edges of the wing should be of a specific vortex generating shape, which is optimized for each airfoil type. In flight tests of the UAV with vortex-active wing were carried out.*

Index Terms—Aerodynamics; unsteady aerodynamic characteristics; vortex generators; vortex active wing.

I. INTRODUCTION

Unsteady Aerodynamics is a high point of state-of-the-art science. Research in this field may lead to many prospective engineering solutions and even discoveries.

Investigations in Unsteady Aerodynamics field are possible only on flying models as unsteadiness does not have a property of motion reversibility. Wind tunnel tests are based on the reversibility principle of motion. Consequently, obtained aerodynamic characteristics are the approximation of the real values. Therefore, the first task to perform a full research program is the necessity to arrange facilities for unsteady research of vortex-active wings. Unmanned aerial vehicle (UAV) with special equipment for aerodynamic research can be used for such tests.

II. VORTEX ACTIVE WING CONCEPT

The concept is based on the research achievements in unsteady vortex flow around the wing at high and supercritical angles of attack. Unsteady flow over the wing starts when the angle of attack is increased more than acceptable.

Then a traditional vortex flow pattern is formed on the upper wing surface in the form of separating vortices at the trailing edge (viscous separation) and separation at the leading edge in the form of a powerful vortex (dynamic separation). Attached vortices are located spanwise (transverse vortices). Trailing vortices propagate downstream (longitudinal vortices). Figure 1 shows a fragment of the unsteady flow around a wing that we obtained in the water tunnel [1].

Transverse vortices are unstable to perturbations on wing surface and sensitive to atmospheric turbulence [2].

At present time micro vortex generators and boundary layer turbulators are used in order to prevent vortex separation on the airfoil. Such turbulators and vortex generators create microvortices and turbulence.

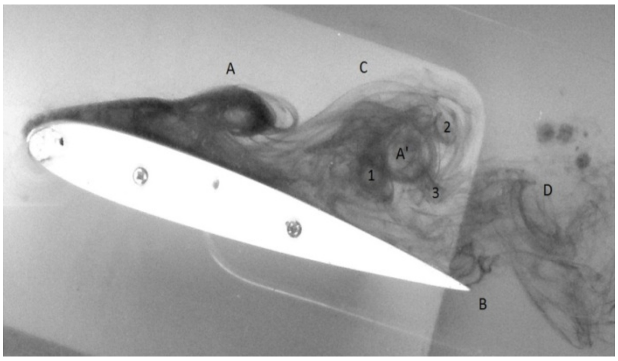

Fig. 1. A part of unsteady vortex flow over rectangular wing in the water tunnel, $\alpha = 15^{\circ}$: *A* is the transverse vortex of dynamic stall; *B* is the formation of the vortex at the trailing edge; *C* is the interaction area between dynamic and viscous vortices; *D* is the vortex burst. Viscous vortices (*1*, *2*, *3*) spin around dynamic vortex (*A*')

In world practice longitudinal vortices, generated by vortex generators, were studied in traditional way, according to reviews and special studies [3] – [6]. In 1990–2000 researches of boundary layer vortex generators have been applied in aircraft industry practice. Nowadays turbulators and vortex generators, which are used on aircrafts, have shape of flat plates, plows, etc., called Vane-Type VGs, Wishbone, Wheel VGs, Low-profile Wheeler's doublet VGs, Forward Wedge, Counter-rotating Vane, Backward Wedge, Single Vane, etc. Turbulators are installed on sport aircrafts Cessna, transport aircrafts Boeing, Embraer, etc. Vortex generators in form of vortilons are used on Embraer aircrafts.

Macrovortex effects on the aerodynamics of supersonic aircraft during takeoff and landing are known. Vortex is created by leading edge extensions. Leading edge extensions are powerful generator of longitudinal vortices [7].

These vortices have large capacity, reach trailing edge and increase maximum lift from 0.5 to 0.65, aerodynamic quality from 3.75 to 4.5 at angle of attack 12º. Furthermore, leading edge extensions influence longitudinal moment, which depends on the area of the extension. This data presented in researches by “Northrop” and TsAGI [8], [9]. In 1980s a monograph, summarizing researches in management of vortices generated by leading edge extensions, edited by G.S. Byushgens was published [7]. A famous aerodynamic TsAGI scientist K. K. Fedyayevskyi also should be mentioned. In 1971 he published a paper [10] in which indicated that the axial velocity in longitudinal vortex generated by leading edge extension is more than the velocity of flight by 50 % on the wing with leading edge of special form.

The analysis of the macrovortex unsteady flow around wing, taking into account vortex generators and turbulators influence on unsteady vortex flow characteristics is carried out. Macrovortex flow around the wing with vortex generators on the leading and trailing edges is experimentally studied in wind tunnels and on flying model [12]. This is the basis for a conceptually new approach to the design of aircraft wings, wind turbines, turbine blades.

Vortex generators on the leading edge of the wing create helical spiral flow over the wing, which is energetically more powerful than microvortices created by turbulators (Fig. 2). As a result, on the upper surface of the wing unsteady longitudinal vortex flow is organized, which divides separation vortices of dynamic and viscous origin. This leads to an increase in the critical angle of attack by 30–40 % and lift coefficient by 10–15 %, stabilization of longitudinal moment by angle of attack, elimination of the hysteresis effect and improves control surfaces operation, preserving their effectiveness at high angles of attack. At the same time the optimum flight angle of attack and aerodynamic quality vary slightly as a result of the suction force and reduction of frictional drag [13].

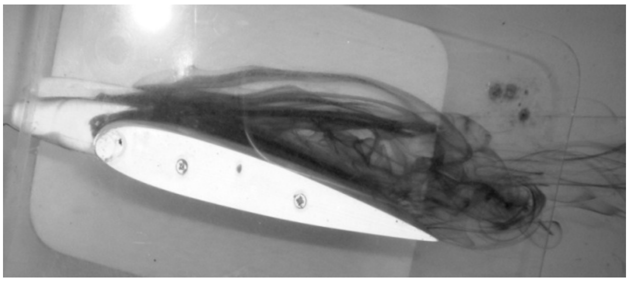

Fig. 2. A part of unsteady flow over the wing with vortex generator on the leading edge, α = 15º

Vortex active wing allows to reduce negative effects of vertical gusts, retains stability at high angles of attack and protects control surfaces from flutter. At supersonic speeds nose vortex generators will provide subsonic flow around leading edge of the wing. Organization of a fundamentally new type of unsteady flow over the wing can be optimized for each particular profile by computer solution of the Navier–Stokes equations for the flow with a given condition and the apparent viscosity of the helical flow (coincidence of streamlines and vortex lines on the wing).

Vortex-active wings differ from the conventional wings by vortex flow pattern, organized by the means of vortex generators, which improve aerodynamic characteristics at high angles of attack, increase critical angle of attack up to 50 % and lift up to 10 %, while static hysteresis is absent. Aerodynamic drag can be reduced by installation of bulky leading-edge vortex generators, which create suction force.

III. RESEARCH BASE

Unlike the widely used modern methods of influence on separated flows by micro-vortex generators (vortex generators within the boundary layer), the proposed method is based on the twisting of the potential flow at the leading edge of the wing with energy transfer into the boundary layer of the wing by helical unsteady flow. It dramatically changes the conventional model of flow around the wing with attached transverse tip vortices.

The basis of the research program is the concept of flow pattern change of the finite span wing. Traditional transverse vortex separation flow at critical angles of attack is replaced by organized unsteady flow with longitudinal vortices which are generated by vortex generators on the leading edge of the wing and use the potential flow energy.

Implementation of the method of longitudinal vortex flow organization is based on the property of vortex generators to produce unsteady helical motion as a result of vortical and translational flows.

The improvement method of traditional flow around wing at high angles of attack is realized by vortex generator with unique features.

Optimized properties of the leading-edge vortex generators should be investigated on conventional airfoils. However, in the long term it is necessary to develop a new kind of specialized vortex-active airfoils with specific aerodynamic characteristics.

IV. PROMISING RESEARCH PROBLEMS

The next tasks can be accomplished by means of vortex-active wing and empennage:

– increase the critical angle of attack up to 50 %, which guarantees flight safety in strong wind gusts (especially important for weatherproof UAV);

– eliminate aerodynamic hysteresis that simplifies piloting at critical angles of attack;

– reduce dynamic loops of aerodynamics characteristics during unsteady oscillation motion of the wing;

– reduce induced and vortex drag at high angles of attack;

– exclude wing autorotation and aircraft spin at high angles of attack;

– improve ailerons and rudders control characteristics;

– eliminate wing trailing edge flutter;

– improve flaps effectiveness;

– improve the aerodynamic performance in rain and icing conditions;

– eliminate the separation and reverse flow zones on helicopter blades;

– improve stability of tiltrotor aircraft transition;

– reduce interference drag between airframe structures;

– improve stability and control of "canard" aircraft with vortex-active foreplane;

– improve the effectiveness of horizontal and vertical tail;

– stabilize the momentum characteristics of longitudinal and lateral motion of the aircraft;

– improve takeoff and landing performance, expanding the exploitation range of short takeoff and landing aircraft;

– reduce the landing speed of the aircraft up to 10 % or more.

V. RESULTS

Vortex-active wings investigation in static conditions is performed in National Aviation University wind tunnels: subsonic wind tunnel TAD-2 (closed test section 4.0 × 2.5 m, maximum speed up to 40 m / s, turbulence intensity 0.9 %); educational wind tunnel UTAD-1 (test cross-section 0.8 × 0.8 m, maximum speed up to 30 m / s); educational wind tunnel UTAD-2 (elliptical test section 0.8 × 0.6 m, maximum speed up to 30 m / s, equipped with electronic measuring system).

The wing with the vortex generators on the leading edge was tested in the wind tunnel UTAD-2 at Re = 2×10^5. The wing dimensions: 400 × 150 mm, aspect ratio 2.66, thickness 16 %. The airfoil has sharp stalling characteristics. At the angle of attack 18° the flow separation at the leading edge occurs and C_L drops by 40 %.

Vortex generators were made in the form of fairings on the leading edge. The design surfaces of the vortex generators have the same airfoil as the wing itself. The dimension of vortex generators vary in the limits (dimensions are presented in percents from the airfoil thickness *c*): width *b* = 30–70 %, length *L* = 20–60 %.

In order to determine the influence of vortex generators on dynamic characteristics of the wing the tests on the oscillating machine OP-2 were carried out in the wind tunnel TAD-2 at Reynolds number (Re) = 0.74 ... 1.15×10^6. Dynamic experiments carried out at two angles of attack with oscillation magnitude ± 2.5°. The angles of attack were chosen as 9.9° for linear dependence of $C_L = f(\alpha)$ and 22.6° for non-linear dependence in critical angles of attack zone. The research was done at various flow speeds and oscillation frequencies for the future analysis of the influence of oscillation motion on aerodynamics characteristics depending on Re and Sh.

The models of the UAV with vortex generators were tested in the wind tunnel TAD-2 [12]. (Fig. 3) Unsteady aerodynamic characteristics of the wing with vortex generators installed on the leading edge are of special interest for the development of automatic control systems. [11]

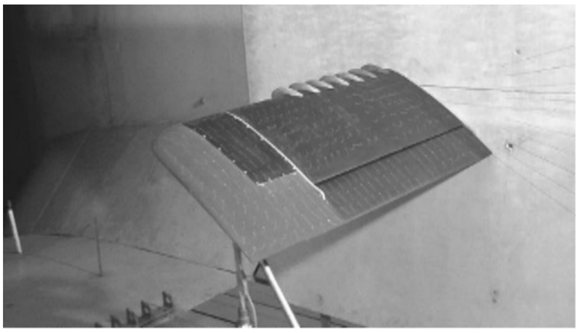

Fig. 3. The wing with vortex generators in wind tunnel TAD-2

The numerical models of drag and lift for the oscillating wing were confirmed as a result of the wind tunnel tests.

$$C_L = C_{L_0} + C_L^{\alpha}\alpha + C_L^{\dot{\alpha}}\dot{\alpha} + C_L^{\ddot{\alpha}}\ddot{\alpha},$$

$$C_D = C_{D_0} + C_D^{\alpha}\alpha + C_D^{\dot{\alpha}}\dot{\alpha} + C_D^{\ddot{\alpha}}\ddot{\alpha}.$$

Figure 4 shows dynamic loops in changes of the coefficients C_D and C_L of the wing without (*a*) and with vortex generators (*b*). Maximum values of C_D significantly decrease at high angles of attack due to presence of vortex generators.

At flight angles of attack the changes are insignificant (Table I).

Figure 5 presents the result of static tests of the finite span rectangular wing (*L* = 400 mm, *c* = 0.15, b_a = 150 mm) with asymmetrical vortex generators. The characteristics of the wing with and without vortex generators are compared.

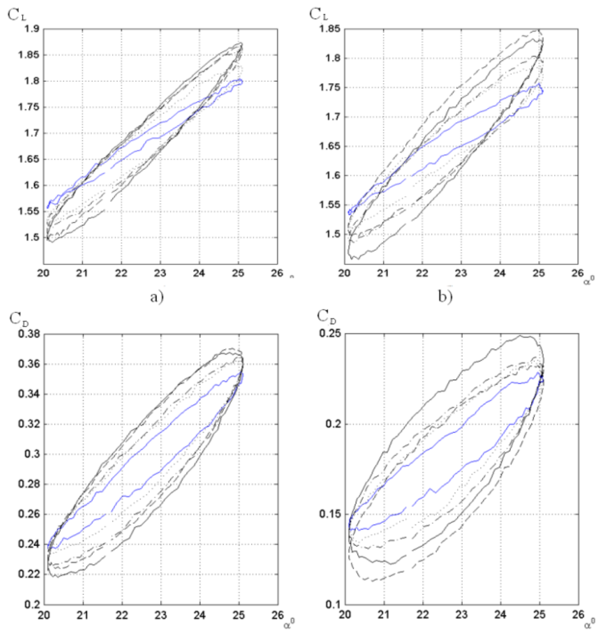

Fig. 4. Dynamics loops of the coefficients C_L and C_D beyond stall angles of attack of the wing without and with vortex generators

TABLE I

CHANGES IN C_D OF THE WING WITHOUT AND WITH VORTEX GENERATORS (VG) AT DIFFERENT ANGLES OF ATTACK

Angle of attack, α	$C_{D\alpha}$
12°	0.11 (without VG)
12°	0.075 (with VG)
25°	0.36 (without VG)
25°	0.24 (with VG)

Aerodynamic drag at flight angles of attack is insignificantly lower with vortex generators. Similarly, the changes in the lift coefficient are insignificant. The static hysteresis, which occurs beyond stall angles, is eliminated with the help of vortex generators. The values of the lift coefficient rise smoothly over 30º without flow separation.

Polar shows that zone of second mode of flight increases significantly with the presence of vortex generators.

Figure 6 shows the process of optimisation of asymmetrical vortex generators position on the wing with flow separation control with the help of tufts.

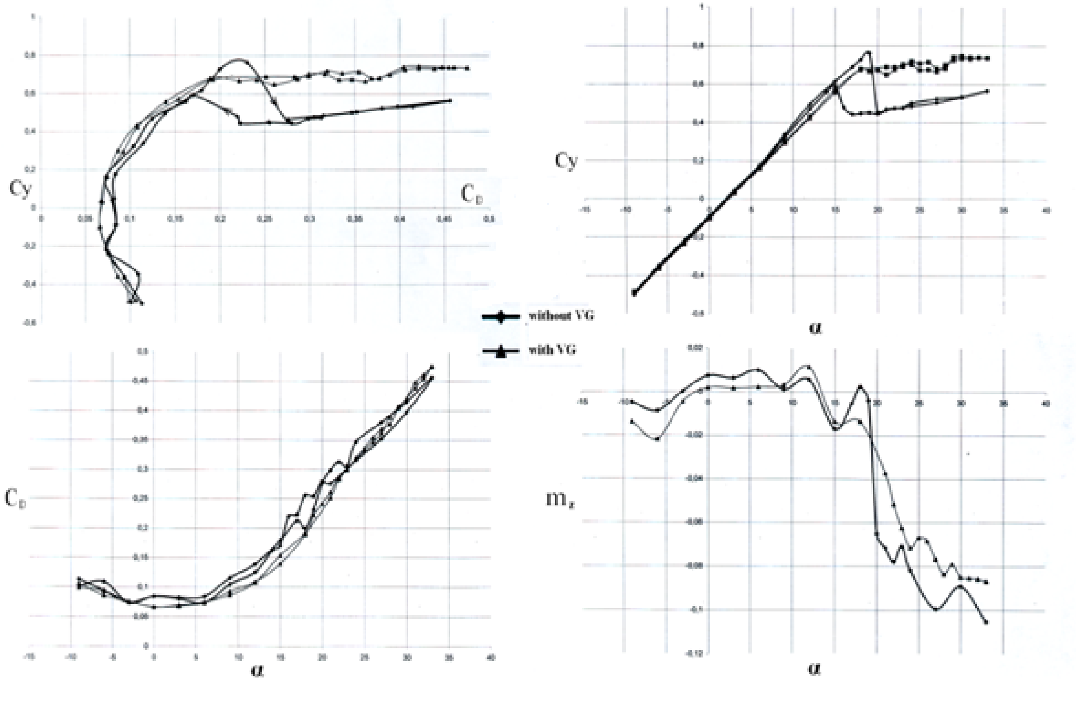

Fig. 5. Aerodynamic characteristics of the wing with vortex generators at supercritical angles of attack

Figure 7 shows the UAV with vortex active wing before the first flight.

On 03/12/2013 the first flight of the UAV with vortex-active wing was accomplished (Published on NAU website http://nau.edu.ua/). Aerobatics and gliding program was demonstrated.

Static characteristics of different airfoils and unsteady characteristics of the oscillating supercritical wing (1.7 m span and 0.6 m chord.) were studied in TAD-2 wind tunnel.

Research results of unsteady wing motion were a base for PhD thesis defended by A. G. Shcherbonos in 2012.

During research in static conditions different vortex generators (see patents) and aerodynamics of the wing with vortex generators at high angles of attack were investigated. This research was generalized in thesis prepared for the defence by S. I. Alieksieienko in 2015.

Fig. 6. UAV wing in the UTAD-2

VI. CONCLUSION

Research results of vortex active flow around the wing are presented in [13], [14] and patented [15] – [18]. This research shows the feasibility of creation of series of vortex-active wings to ensure the flight safety of UAVs at supercritical angles of attack. Obtained results are necessary for the development of automatic control systems of UAVs at high angles of attack.

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Fig. 7. UAV before the first test flight

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Є. П. Ударцев, С. І. Алєксєєнко, О. О. Жданов. Нестаціонарна аеродинаміка вихороактивного крила безпілотного літального апарату на великих та закритичних кутах атаки

Концепція полягає в тому, що обтікання крила формується у вигляді нестаціонарного поздовжньо-вихрового обтікання. Форми передньої та задньої кромок перспективних крил мають бути специфічної вихороутворюючої форми, яку оптимізовано конкретно для кожного профілю крила. Проведено льотні випробування безпілотного літального апарату з вихороактивним крилом.

Ключові слова: аеродинаміка; нестаціонарна аеродинаміка; вихороутворювач; вихороактивне крило.

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Е. П. Ударцев, С. И. Алексеенко, А. А. Жданов. Нестационарная аэродинамика вихреактивного крыла беспилотного летательного аппарата на больших и закритических углах атаки

Концепция состоит в том, что обтекание крыла формируется в виде нестационарного продольно-вихревого обтекания. Формы передней и задней кромок перспективных крыльев должны быть специфической вихреобразующей формы, которая оптимизирована конкретно для каждого профиля крыла. Проведены испытательные полеты беспилотного летательного аппарата с вихреактивным крылом.

Ключевые слова: аэродинамика; нестационарная аэродинамика; вихреобразователь; вихреактивное крыло.

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