Aerodynamics of unmanned aerial vehicle with three lifting surfaces

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SUMMARY

Unconventional aircraft configuration allows obtaining better aerodynamic characteristics, however a list of shortcomings come up in the engineering process. The possible resolution of these shortcomings is presented using the example of developed unmanned aerial vehicle (UAV) of three lifting surface configuration with new type of leading-edge vortex generators (LEVGs). This paper presents the effect of LEVGs installation on the foreplane and elaborates on shortcoming resolution and gained advantages in aerodynamic characteristics. CFD simulation results of foreplane with LEVGs are outlined.

KEY WORDS: aerodynamics, unmanned aerial vehicle, leading-edge vortex generators, lifting fuselage, CFD.

1. INTRODUCTION

Production and exploitation of unmanned aerial vehicles rapidly grow. At the same time complexity and scope of unmanned aerial vehicles tasks increases. Further enhancement of their aerodynamic characteristics and performance is of a great importance as it allows operators to extend time, range and environmental conditions. New achievements and developments of applied aerodynamics can be easily tested on UAVs.

Enhanced aerodynamic characteristics may be achieved for unconventional aerodynamic configurations. However, variety of issues comes up in engineering process of aircraft with such a configuration. In order to demonstrate possibility of successful design of aircraft with unconventional configuration and implementation of new type of leading-edge vortex generators it was decided to develop medium-altitude long-endurance UAV. The UAV M-7B5, which was developed, manufactured and tested in National Aviation University was chosen as a prototype, see Figure 1.

Figure 1. Unmanned aerial vehicle M-7B5

Currently most of all aircraft and unmanned aerial vehicles are developed based on conventional aerodynamic configuration. In such a configuration horizontal stabilizer produces negative lift of considerable value. Consequently the wing to eliminate negative lift must have larger area, resulting in higher friction force. The other important fact is that the angle of incidence of stabilizer is not optimal. Such configuration therefore does not provide maximum aerodynamic quality.

Increased flight range of an unmanned aerial vehicle can be provided by means of a configuration which provides high lift-to-drag ratio. Canard configuration or its modifications can be utilized to meet this requirement if their weaknesses are eliminated.

Canard is aerodynamic configuration, in which the aircraft has longitudinal control surfaces located in front of the wing. Wing, center of pressure of which is located behind the center of gravity of the aircraft, produces a stabilizing moment, while the foreplane produces destabilizing moment. The forplane is movable. Unlike the conventional this configuration has no balancing drag. However canard configuration is almost not used in civil aviation and rarely used for mass-produced unmanned aerial vehicles due to a number of shortcomings. However there is a successful example of multiple lifting surfaces aircraft.

Piaggio P.180 Avanti (II) is an Italian executive aircraft with three lifting surfaces: the front fixed wing of small area, the main wing and aft horizontal stabilizer. This configuration provides increased longitudinal stability, control and reliability comparing to an aircraft with two lifting surfaces. Three-lifting-surface configuration provided a 34% reduction in the total area of the wing comparing to the traditional configuration, thus reducing weight and friction drag. Moreover, Piaggio P.180 Avanti II is the fastest among all turboprop aircraft in its category [1].

More advanced than canard three-lifting-surface configuration was therefore chosen for the development of unmanned aerial vehicle. However, unlike Piaggio P.180 Avanti, aircraft will have more advanced design with movable foreplane with leading-edge vortex generators.

The structure of this paper is as follows: in Section 2 based on the conducted analysis we elaborate on the shortcomings of configurations with several lifting surfaces and propose solutions to resolve them; in Section 3 the development process of unmanned aerial vehicle is presented; CFD investigation of leading-edge vortex generators is outlined in Section 4.

2. PROBLEM STATEMENT AND PROPOSED SOLUTION

2.1. Shortcomings analysis

Based on the analysis of NASA [2.3] and other academic institutions research, we can specify the following disadvantages of configuration with several lifting surfaces comparing to the conventional configuration:

1) foreplane’s stall at high angle of attack causes drop. During the landing such a nose-drop leads to a strong stroke of landing gear’s front shock strut, which significantly reduces its lifetime or causes shock strut breaking;

2) main wing flaps produce pitch moment and foreplane’s angle of incidence must be increased to compensate it. It leads to stall, especially in vertical gusts. On practice it imposes limitations of the maximum flaps deflection, decreasing takeoff and landing performance;

3) flow around part of the wing has downwash caused by foreplane, reducing an angle of attack and the lift coefficient of the wing;

4) wing angle of attack be limited to prevent stall from a wing, which leads to pitch instability of the aircraft and may be irreversible;

5)	foreplane operates in lower Reynolds number due to small chord length comparing to the main wing, which leads to decreased foreplane's efficiency and stall characteristics;

If the impact of shortcomings is reduced and aircraft is optimized, higher aerodynamic quality can be achieved and consequently fuel efficiency and flight range will be considerably higher than in the conventional configuration.

2.2. Proposed solutions

To resolve first, second and fifth problems it is proposed to install a device that will increase foreplane's critical angle of attack. These devices include: turbulators (micro-vortex generators), vortex-generators, vortilons and wing fences for swept wings. It leads to improved aerodynamic characteristics at high angles of attack.

In paper [4] various types of leading-edge vortex generators in comparison with broadly used in aviation vortex generators (turbulators) were investigated in the low speed wind tunnel. In Figure 2 lift-to drag ratio for different vortex generators is presented. Flight test were also conducted and proved the effectiveness of LEVGs on leading edge of the wing.

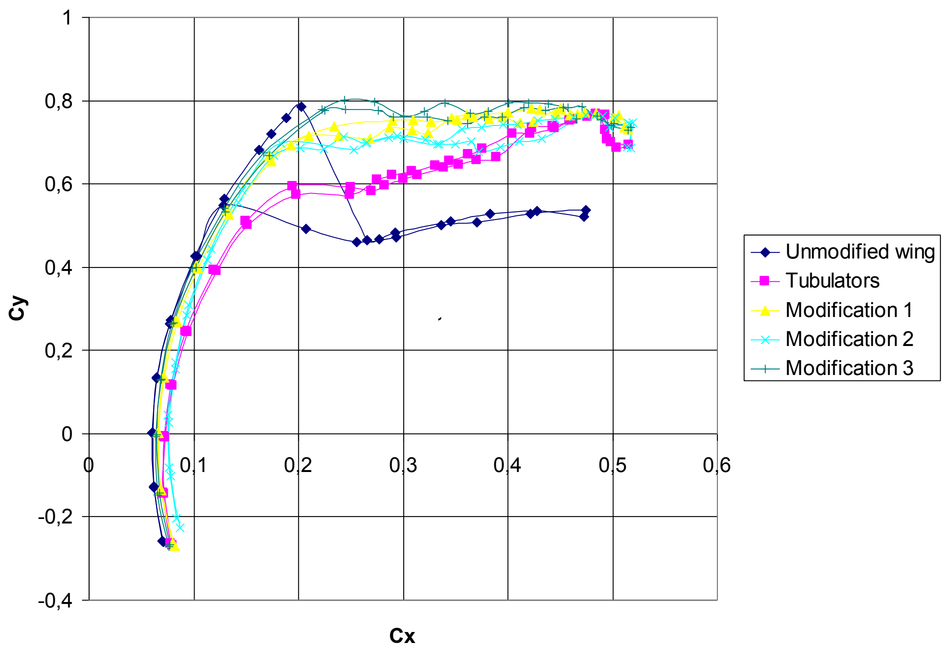

Figure 2. Lift-to drag ratio for unmodified wing, wing with turbulators and three types of vortex generators

It was revealed that wing has a large hysteresis of aerodynamic characteristics at critical angles of attack. In other words, aircraft's lift at 10°-18° angles of attack during returning to cruise angles of attack after wing stall is significantly lesser, which is especially dangerous at low altitudes. Leading-edge vortex generators eliminate hysteresis loops and considerably more effectively prevent wing stall than conventional vortex generators (turbulators). They also produce less additional drag due to decreased pressure on the leading edge of the wings, having almost no influence at lift-to-drag ratio at cruise angles of attack.

It was therefore decided to install a row of leading-edge vortex generators, which form a vortex slat [5] on the swept foreplane. It will increase the critical angle of attack and delay stall for about 20 degrees. This allows resolving shortcomings which are a fundamental obstacle in configurations with several lifting surfaces utilization.

The large area of wing is ahead of the propeller. It helps to improve stall characteristics and extend laminar flow area more by means of propeller’s suction.

The third shortcoming resolving was achieved by means of high wing type application. Foreplane´s position is determined in such way that wing is not in flow behind foreplane during cruise and take-off.

3. DEVELOPMENT OF THE UAV

3.1. Preliminary design of the UAV

Determination of the wing, foreplane and fuselage relative position was carried out in accordance with the two basic equations. The first equation is the equation of wing, foreplane and fuselage lift equality to aircraft weight in cruise is as follows:

$$m \cdot g = Y_{WING} + Y_{FOREPLANE} + Y_{FUSELAGE}$$

where, m is a weight, g is gravitational acceleration, Y_{WING} is wing lift, $Y_{FOREPLANE}$ is foreplane lift, $Y_{FUSELAGE}$ is fuselage lift.

The second equation is the equation of aircraft balance at cruise angle of attack with maximum aerodynamic quality , which is preliminarily supposed to be equal to 6˚:

$$M_{z_{UAV}} = M_{z_{WING}} + M_{z_{FOREPLANE}} + M_{z_{FUSELAGE}}$$

where $M_{z_{UAV}}$ is total UAV pitching moment, $M_{z_{FOREPLANE}}$ is foreplane’s pitching moment, $M_{z_{FUSELAGE}}$ is fuselage’s pitching moment.

If fuselage lift and centre of lift are known these equations allow obtaining wing and foreplane’s area. In next sections it is explained how fuselage, wing and foreplane characteristics were found.

3.2. Lifting fuselage design

The following specific requirements were specified for fuselage:

1) sufficient space for passengers, fuel tanks, equipment, foreplane fastening, landing gear, wingbox;

2) shape optimization and obtaining of additional lift by fuselage.

3D models of three fuselages based on the Wortmann airfoils with different thickness were created in SolidWorks. As a result of CFD simulations of flow around fuselage by means of SolidWorks Flow Simulation tool the most effective one was determined and is shown in Figure 3.

Afterwards a number of computer-aided simulations were conducted and all necessary fuselage aerodynamic characteristics such as centre of pressure $X_{c.p}$ and fuselage lift $Y_{FUSELAGE}$ were obtained. Developed fuselage provides 5% from total lift at cruise angle of attack $\alpha = 6^{\circ}$.

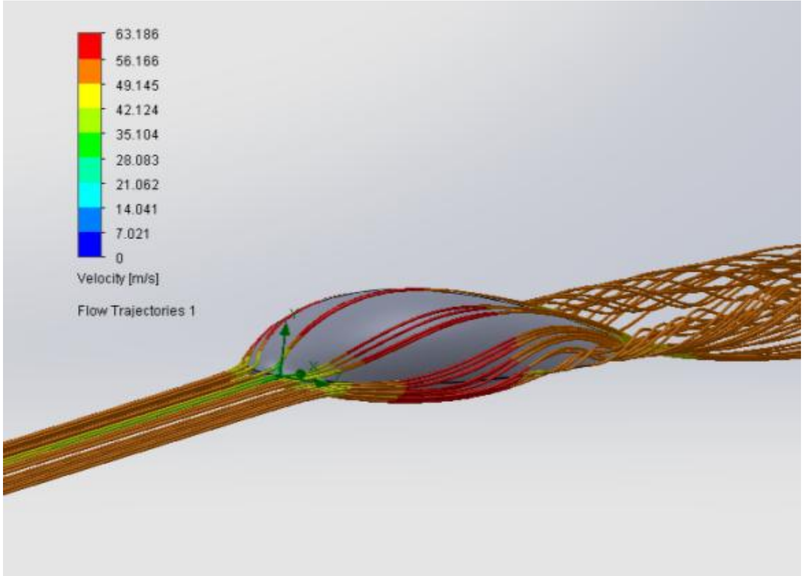

Figure 3. Flow trajectories and velocity distribution for the chosen fuselage

3.3. *Laminar wing design*

A tapered wing with high aspect ratio is chosen for the aircraft. FX 61-184 airfoil with high thickness $\bar{c} = 18{,}4$ and high lift-to-drag ratio $K = 131.1$ at $\alpha = 6°$ ($Re = 1{,}000{,}000$) is chosen as an airfoil. For an aircraft with lifting fuselage high optimum angle of attack is desirable.

Wing blowing by tractor propeller leads to higher lift coefficient C_L but eliminates advantages of the laminar flow. That is why pusher propeller was implemented. It extends laminar area even more by flow suction, reducing drag and improving fuel efficiency. Moreover it helps to prevent stall from the main wing.

It was proposed to evaluate pusher propeller effect using existing data. The initial data for calculation was taken from paper [6]. Laminar flow area and stall angle was recalculated from above-mentioned data using ratio between experimental thrust coefficient and thrust coefficient of the developed UAV.

4. CFD INVESTIGATION OF FOREPLANE WITH LEADING-EDGE VORTEX GENERATOR

In order to prove leading-edge vortex generators effect on separation liquidation, understand underlying physical concepts of vortex flow and optimize LEVGs shape CFD investigation was carried out.

The leading-edge vortex generator has complex geometry. As a result, automatic mesh in Solidworks Flow Simulation and ANSYS ICEM cannot be properly conducted and has high number of distorted elements. Tetrahedral mesh without distorted elements was created manually in ANSYS ICEM. Mesh for unmodified foreplene has 1441050 elements, while one LEVG installed on the foreplane increases elements number up to 3772538. That is why effect simulation strategy using one vortex generator was chosen.

The CFD simulation of foreplane with vortex generator was conducted in the software package ANSYS CFX. Shear Stress Transport turbulence model was used. The data for the numerical experiment is wing area S_{wing}, atmospheric pressure for 0 m. altitude P_0 , undisturbed flow velocity V_0, and its components V_x, V_y for the angles of attack of 6˚, 10˚, 12˚, 14˚, 16˚, 20˚, air temperature T_0. The following data was determined: lift F_{ya}, drag F_{xa}, lift coefficient C_{ya}, drag coefficient C_{xa}.

As a result, it was proved that vortex flow past vortex generator is created. Thus turbulence is not the only reason for separation resistance. Figure 4 represents vortex flow. It transfers particles with high kinetic energy into the boundary layer, energizes it and improves flow separation resistance. That is the reason of such vortex generators effectiveness comparing to other types. The ways to optimize shape of LEVGs were determined.

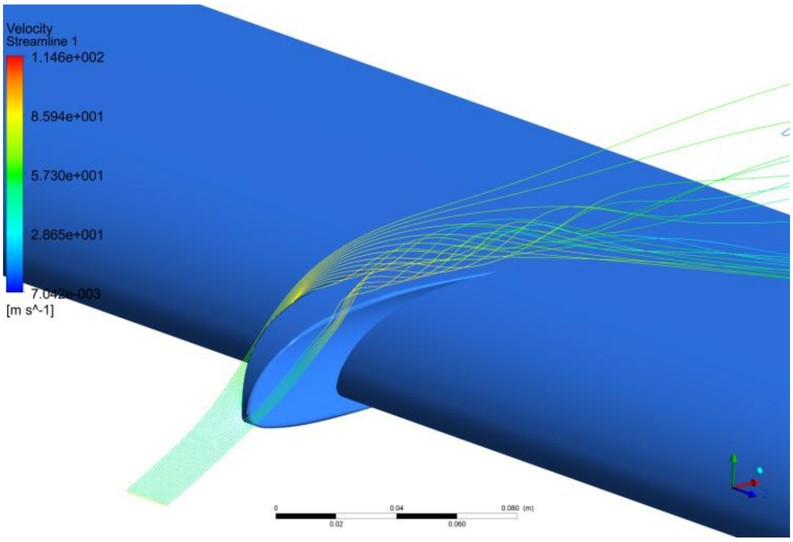

Figure 4. Flow around LEVG installed on the foreplane

5.CONCLUSIONS

The shortcomings of multiple lifting surfaces aircraft were overcome and problems of strong vertical wind gusts were resolved. New type of leading-edge vortex generators was implemented on the UAV’s foreplane and CFD simulation of wing with vortex generator was carried out.

The demonstrated technologies allow UAV to obtain high aerodynamic quality, increase flight range, stability, improve autonomy and resistance flow separation and wind gusts comparing to Elbit Hermes 450, AAI RQ-7 Shadow, M-7B5.

The interaction of vortexes created by vortex generators and wing tip vortex is of great interest. These vortices may interact in such way that induced drag is decreased, which can positively affect aircraft aerodynamics qualities. Further investigation of leading-edge vortex generators will be conducted.

REFERENCES

1. George F. Piaggio Aero P180 Avanti II. *Business & Commercial Aviation*, September 2007 pp. 116-125

2. Anderson S. B. «A Look at Handling Qualities of Canard Configurations», NASA Technical Memorandum 88354, Ames Research Center, California, September 1986

3. Gloss B.B., McKinney L.W. «Canard-wing Lift Interference Related to Maneuvering Aircraft at Subsonic Speeds», NASA Technical Memorandum X-2897, NASA, Washington, D.C, December 1973

4. Udartsev E.P., Alekseenko S.I., Sattarov A.I. «Improvement of UAV navigation reliability at high angles of attack», 3rd International Conference Methods and Systems of Navigation and Motion Control Proceedings, Kyiv, Ukraine, 2014, pp.40-43

5. E.P. Udartsev, S.I. Alekseenko, M.P. Matijchik Patent of Ukraine №20130891 Vortex slat. №23050/ZU/13. from 23.10.2013 (in. Ukrainian)

6. Catalano F. M. «On the Effects of an Installed Propeller Slipstream on Wing Aerodynamic Characteristics», Acta Polytechnica Vol. 44 No. 3, 2004