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DEVELOPMENT OF SMALL ELECTRIC FIXED-WING VTOL UAV

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Abstract:

During last years, along with development of electric propulsion systems, developments of multi-rotor unmanned aerial vehicles (UAV) are pushed strongly. The main benefits of this concept of UAV over standard helicopters are mechanical simplicity, decoupled dynamics and cheaper manufacturing, especially in small dimensions. On the other side, multi-rotor vehicles are less efficiency than fixed-wing vehicles, especially for long-distance flight. The traditional fixed-wing UAVs can fly for long distances, but they require runways for take-off and landing. By combining vertical take-off and landing (VTOL) capabilities of multi-rotor vehicles and energy efficient long-distance flight of fixed wing vehicles, new type of UAVs is involved: VTOL UAV. This paper presents development of small electric powered fixed-wing VTOL UAV. This aircraft is the part of the project of large hybrid VTOL UAV by company EDePro and it is intended to be technology demonstration model and platform for testing VTOL and transition capabilities as well as autopilot and other systems and subsystems development.

Key words: VTOL UAV, Development, Electric propulsion.

1. Introduction

In recent years, the number of unmanned aerial vehicles (UAVs) is in expansion, especially in the field of small UAVs. Today, UAVs exist in a various sizes and with wide ranges of performances, starting from micro UAVs with dimensions of 10 cm x 2.5 cm with mass of 16 g (Black Hornet Nano), to the large UAVs like RQ-4 Global Hawk with mass of 15000 kg and capabilitiy to long range flight. For now, the most massive use of UAVs is in military and for recreational purposes, but their usage in commercial flight is increase over years. Application field of UAVs is very wide: transport, surveillance, information gathering, performing operations which are potentially dangerous for humans etc. For now, the most massive use of UAVs is in military and for recreational purposes, but their usage in commercial flight is increase over years. Application field of UAVs is very wide: transport, surveillance, information gathering, performing operations which are potentially dangerous for humans etc.

Multi-rotor type of UAVs is now widely used due to their control simplicity, maneuverability and ability for vertical take-off and landing (VTOL). On the other side, main disadvantage is energy consumption during cruise which results in relatively short operational time. Classical, fixed-wing UAVs provide much larger energy efficiency during cruise, but they require runways for take-off and landing. Taking into account advantages of both types, the solution is to have a hybrid configuration, with VTOL abilities like multi-rotor UAVs and energy efficiency during cruise like fixed-wing UAVs. This hybrid configuration can be obtained by integration of multiple rotors to the fixed-wing UAVs.

During last years, the interest in electric propulsion systems for aircraft has grown considerably. Main benefits of the electric propulsion are clean energy, low noise level, low mass of electric motors. On the other side, specific energy density of batteries, which are applied as energy source in electric propulsion, is much lower than of kerosene, up to 60. According to many scientific and general publications, energy density of batteries will be increased in next ten years making the electric propulsion competitive with conventional propulsion [1].

This paper presents development of small electric powered fixed-wing VTOL UAV. Name of this aircraft is ALECS, which presents the acronym of "**A**dvanced **L**ight **E**lectrical **C**omposite **S**ystem". ALECS has four fixed motors for its vertical propulsion, which are attached to the fixed wing platform making quad-copter configuration and a single motor for the horizontal propulsion. Also, in presence of runway, ALECS has ability for conventional take-off and landing, in order to save the energy from batteries. This aircraft is part of project of large hybrid VTOL UAV by company EDePro and it is intended to be technology demonstration model and platform for testing VTOL and transition capabilities as well as autopilot and other systems and subsystems development.

2. Specifying requirements

The ALECS VTOL is designed to be able to take off and landing both, conventionally and in quad-copter mode. During design some basic requirement are taken into account such as: low cost, capability to take off and landing in both quad-copter mode (vertical) and conventionally, hovering capability, ability to be equipment with different kinds of payloads such as imaging equipment, gimbals, etc., ease packaging and transportation. The weight of payload is up to 6 kg. Mission profile of the ALECS is:

1. Vertical take-off and vertical climbing to 500 m height with velocity of 4 m/s (quad-copter mode),
2. Transition from vertical to horizontal flight (quad-copter mode + horizontal flight mode),
3. Cruise and loitering with velocity of 100km/h to distance of 50 km (horizontal flight mode),
4. Transition from horizontal flight to hovering (quad-copter mode + horizontal flight mode)
5. Hovering in duration of 5 min (quad-copter mode),
6. Transition from hovering to horizontal flight (quad-copter mode + horizontal flight mode)
7. Come back to the ground station with velocity of 100 km/h (horizontal flight mode),
8. Transition from horizontal to vertical flight (quad-copter mode + horizontal flight mode),
9. Vertical landing with velocity of 2 m/s (quad-copter mode).

Maximal cruise velocity is 200 km/h while minimal cruise velocity is 42 km/h. After analyzing flight mission profiles of similar fixed-wing VTOL UAVs (Panther, ALTI Transition, Trinity, Tron, TURAC [2]), estimated take-off weight of the ALECS is 35 kg. The initial sketch is shown in the Figure 1.

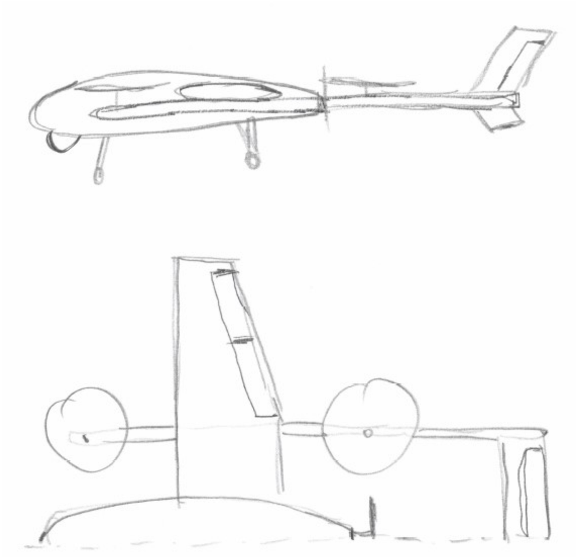

Fig. 1. The initial sketch of the ALECS VTOL.

3. Airfoil and wing geometry

According to the estimated weight, length of the wing chord is expected to be in range 0.22 m – 0.6 m. Taking into account cruise velocity of 100 km/h, Reynolds numbers are in the range of 200000 – 550000, which belong to small Reynolds numbers. Due to that, airfoil SD7090 is selected for the wing. The Figure 2(a) presents lift curve of airfoil SD7090 without flap while the Figure 2(b) presents lift curve same airfoil with plain flap which relative chord is 0.25 for 10º, 20º, 30º and 45º deflection angles. Both analyses are performed for Reynolds numbers between 200000 – 550000. The area of the wing will be determined according to the wing loadings in cruise and at stall velocity.

The wing loading in cruise can be calculated as follows

$$\left(\frac{W}{S}\right)_{\mathrm{cr}} = \frac{1}{2g}\rho V_{\mathrm{cr}}^2 \sqrt{\pi A e C_{\mathrm{D0}}} = 24.5\,\mathrm{kg/m^2}, \tag{1}$$

where ρ presents air density at cruise level, V_{cr} is cruise velocity, A is the aspect ratio of the wing which is set to be 7, e is the Oswald number which is set to be 0.8 [3], and C_{D0} is the zero-lift drag coefficient which is set to be 0.022 [3]. The wing loading at the stall velocity (42 km/h) is

$$\left(\frac{W}{S}\right)_{\mathrm{stall}} = \frac{1}{2g}\rho V_{\min}^2 C_{\mathrm{L\,max}} = 15.56\ \mathrm{kg/m^2}, \tag{2}$$

where the maximum lift coefficient of the wing is calculated for flap deflection angle of 20º (the Figure 2(b)), and obtained value is decreased by 10% [3]: $C_{\mathrm{L\,max}} = 1.78 \cdot 0.9 = 1.6$. The wing area is determined according lower value of wing loading, which is obtained for stall velocity. Since estimated weight is 35 kg, wing area is calculated to be S=2.25 m^2. In that case, wing span is

$$b = \sqrt{AS} = 4\,\mathrm{m}. \tag{3}$$

The wing geometry, including flaperons, is given in the Figure 3.

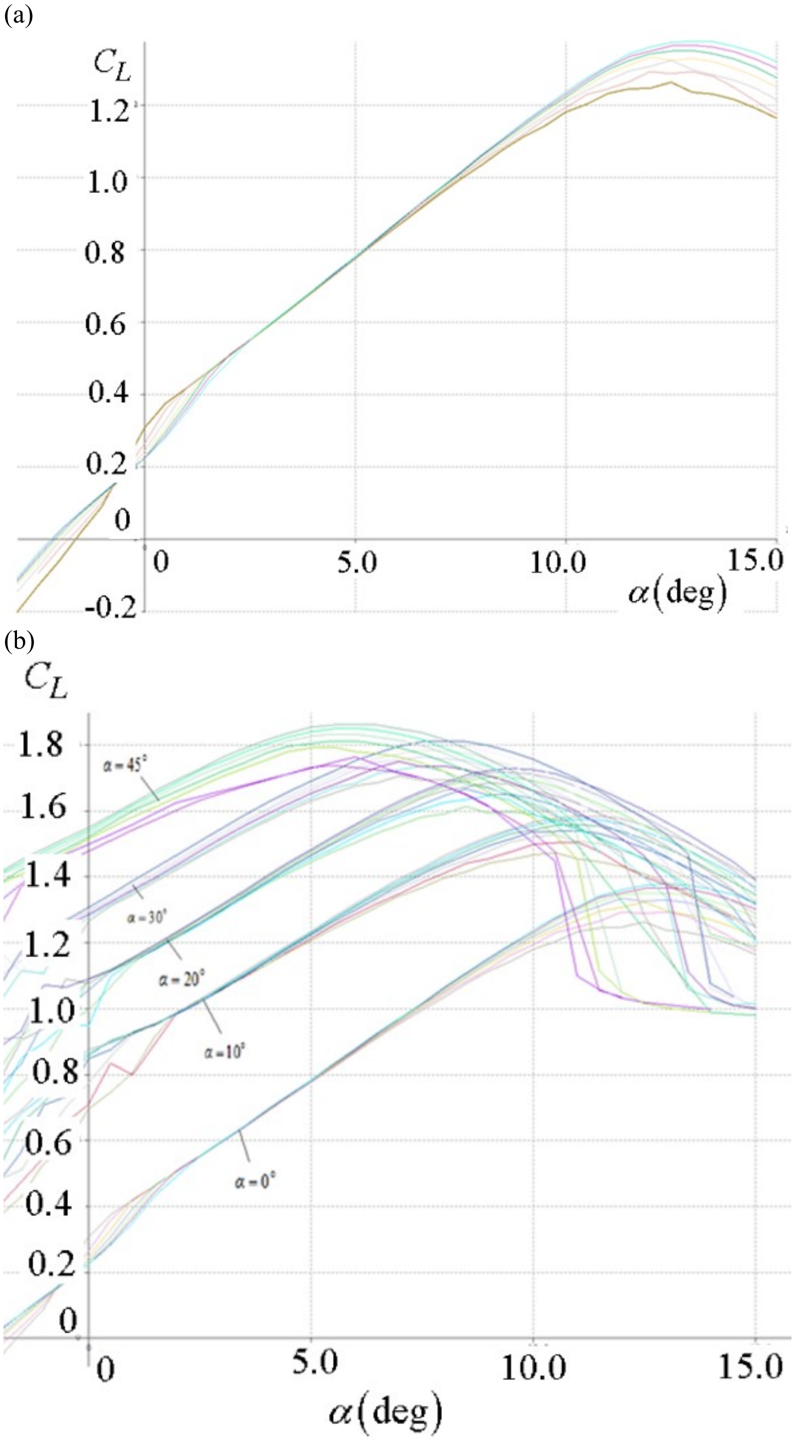

Fig. 2. Lift curve of airfoil SD7090: a) without flap, b) with plain flap with relative chord length 0.25.

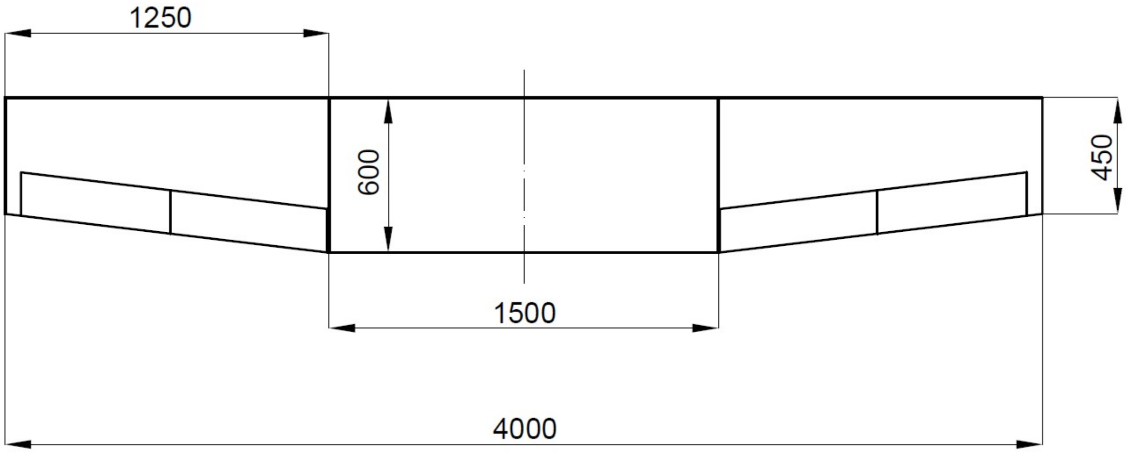

Fig. 3. Dimensions of the wing.

After determination of tails and fuselage dimensions according to recommendations given in [3], the 3D model of the ALECS is obtained and it is presented in the Figure 4.

Fig. 4. The 3D model of the ALECS VTOL UAV.

4. Selection of electric motors and batteries

Power in hovering and vertical climbing can be calculated at the same way as for helicopter, by using the actuator disc theory [4]

$$P_{\mathrm{h}} = T v_{\mathrm{h}}, \; P_{\mathrm{cl}} = P_{\mathrm{h}} \left[\frac{V_{\mathrm{cl}}}{2 v_{\mathrm{h}}} + \sqrt{\left(\frac{V_{\mathrm{cl}}}{2 v_{\mathrm{h}}} \right)^2 + 1} \right], \tag{4}$$

where T presents the thrust, V_{cl} is the climbing velocity during vertical take-off while v_{h} is the induced velocities in hovering which can be calculated as follows [4]

$$v_{\mathrm{h}} = \sqrt{\frac{T}{A}\frac{1}{2\rho}} = \sqrt{\frac{D_{\mathrm{L}}}{2\rho}}, \tag{5}$$

in which D_{L} is disc loading. Power in descending can't be calculated for low velocities by using the actuator disc theory, so this power will be considered to be close by power in hovering. Required power by motors in hovering and vertical climbing is

$$P_{\text{mot-h}} = \frac{P_{\mathrm{h}}}{\eta_{\mathrm{p}}} = \frac{T}{\eta_{\mathrm{p}}}\sqrt{\frac{D_{\mathrm{L}}}{2\rho}}, \quad P_{\text{mot-cl}} = \frac{P_{\mathrm{cl}}}{\eta_{\mathrm{p}}} = \frac{T}{\eta_{\mathrm{p}}} v_{\mathrm{h}} \left(\frac{V_{\mathrm{cl}}}{2v_{\mathrm{h}}} + \sqrt{\left(\frac{V_{\mathrm{cl}}}{2v_{\mathrm{h}}}\right)^2 + 1} \right), \tag{6}$$

where η_{p} presents the efficiencies of propellers. Considering thrust-to-weight ratio to be 1.3, required powers by motors are for hovering and vertical climbing are

$$P_{\text{mot-h}} = \frac{1.3Mg}{\eta_{\mathrm{p}}}\sqrt{\frac{D_{\mathrm{L}}}{2\rho}}, \quad P_{\text{mot-cl}} = \frac{1.3Mg}{\eta_p} v_{\mathrm{h}} \left(\frac{V_{\mathrm{cl}}}{2v_{\mathrm{h}}} + \sqrt{\left(\frac{V_{\mathrm{cl}}}{2v_{\mathrm{h}}}\right)^2 + 1} \right), \tag{7}$$

in which M presents aircraft's weight.

The power drawn from the battery can be obtained as follows

$$\begin{aligned} P_{\text{bat-h}} &= \frac{P_{\mathrm{h}}}{\eta_{\mathrm{p}}\eta_{\mathrm{mot}}\eta_{\mathrm{esc}}\eta_{\mathrm{c}}} = \frac{Mg}{\eta_{\mathrm{p}}\eta_{\mathrm{mot}}\eta_{\mathrm{esc}}\eta_{\mathrm{c}}}\sqrt{\frac{D_{\mathrm{L}}}{2\rho}}, \\ P_{\text{bat-cl}} &= \frac{P_{\mathrm{cl}}}{\eta_{\mathrm{p}}\eta_{\mathrm{mot}}\eta_{\mathrm{esc}}\eta_{\mathrm{c}}} = \frac{Mg}{\eta_{p}\eta_{mot}\eta_{\mathrm{esc}}\eta_{c}} v_{\mathrm{h}} \left(\frac{V_{\mathrm{cl}}}{2v_{\mathrm{h}}} + \sqrt{\left(\frac{V_{\mathrm{cl}}}{2v_{\mathrm{h}}}\right)^2 + 1} \right), \end{aligned} \tag{8}$$

where η_{mot}, η_{esc} and η_{c} present the efficiencies of motor, ESC and cables respectively. For the first estimation, following values of efficiencies can be assumed: $\eta_{\mathrm{p}} = 0.75$, $\eta_{\mathrm{mot}} = 0.9$, $\eta_{\mathrm{esc}} = 0.98$, $\eta_{\mathrm{c}} = 0.98$. The energy drawn from the batteries for hovering and vertical climbing is

$$\begin{aligned} E_{\text{bat-h}} &= P_{\text{bat-h}} t_{\mathrm{h}} = \frac{Mgt_{\mathrm{h}}}{\eta_{\mathrm{p}}\eta_{\mathrm{mot}}\eta_{\mathrm{esc}}\eta_{\mathrm{c}}}\sqrt{\frac{D_{\mathrm{L}}}{2\rho}}, \\ E_{\text{bat-cl}} &= P_{\text{bat-cl}} t_{\mathrm{cl}} = \frac{Mgt_{\mathrm{cl}}}{\eta_{\mathrm{p}}\eta_{\mathrm{mot}}\eta_{\mathrm{esc}}\eta_{\mathrm{c}}} v_{\mathrm{h}} \left(\frac{V_{\mathrm{cl}}}{2v_{\mathrm{h}}} + \sqrt{\left(\frac{V_{\mathrm{cl}}}{2v_{\mathrm{h}}}\right)^2 + 1} \right), \end{aligned} \tag{9}$$

in which t_{h} and t_{cl} present the time spent in hovering and vertical climbing respectively.

In cruise, the required powers by motor for maximum velocity and the power drawn from the batteries can be calculated from equations of steady flight, as follows

$$P_{\text{mot-cr-max}} = \frac{Mg}{F} V_{\text{cr-max}} \frac{1}{\eta_{\mathrm{p}}}, \quad P_{\text{bat-cr}} = \frac{Mg}{F} V_{\mathrm{cr}} \frac{1}{\eta_{\mathrm{p}}\eta_{\mathrm{mot}}\eta_{\mathrm{esc}}\eta_{\mathrm{c}}}, \tag{10}$$

where F presents the finesse. The energy drawn from the battery per aircraft mass in cruise is

$$E_{\text{bat-cr}} = \frac{Mg}{F} V_{\text{cr}} t_{\text{cr}} \frac{1}{\eta_{\text{p}} \eta_{\text{mot}} \eta_{\text{esc}} \eta_{\text{c}}}, \tag{11}$$

in which t_{cr} is the time spent during cruise. Total energy drawn from the battery is

$$E_{\text{bat}} = E_{\text{bat-cl}} + E_{\text{bat-h}} + E_{\text{bat-d}} + E_{\text{bat-cr}}. \tag{12}$$

The energy for vertical descending ($E_{\text{bat-d}}$) will be calculated as for hovering. Weight of batteries can be calculated as follows

$$m_{\text{bat}} = \frac{E_{\text{bat}}}{E^*}, \tag{13}$$

where E^* is the specific energy density of batteries (energy of battery per mass of battery). The energy required for transition will be neglected since time spent during transition is negligible compared to the other flight modes.

Assuming that the finesse in horizontal flight to be 10, the specific energy of battery is 160 Wh/kg and disc loading for two-bladed propeller is $D_{\text{L}} = 200\,\text{N/m}^2$, Table 1 presents the energy drawn from batteries for each segment of flight.

	Vertical take-off and climbing	Cruise	Hovering	Cruise	Vertical descending and landing
Energy from batteries (Wh)	208	736	403	736	336

Table 1. The energy drawn from the batteries for each segment of flight

According to the Table 1, weight of batteries required for quad-copter mode is 5.9 kg, and for horizontal flight mode is 9.2 kg, which gives 15.1 kg. Required power of one motor in quad-copter mode is 1.69 kW (for vertical climbing), and for horizontal flight mode on maximum velocity is 2.54 kW.

After analyzing commercially available electric motors for UAVs, motor Q80-9M V2 produced by “Hacker” is selected for both flight modes. The weight of this motor is 1.035kg and maximum power is 5.5kW. After detail analysis performed by software “eCalc”, available on the web-site of “Hacker”, following propellers are selected: 21x14 for horizontal flight and 27x8 for quad-copter mode, both produced by “Fiala”. According to currents and voltages obtained by “eCalc”, 10 batteries “MultiStar” with 12 Ah, 6S, 10C are chosen. Dimensions of one battery are 183 mm x 77 mm x 56 mm and weight is 1610 g, which implies that equal weight of batteries is 16.1kg, which is coincides with performed calculation.

The Figure 5 present thrust and torque versus revolute per minute (rpm) of motor Q80-9M V2 with 27x8 propeller obtained after static testing.

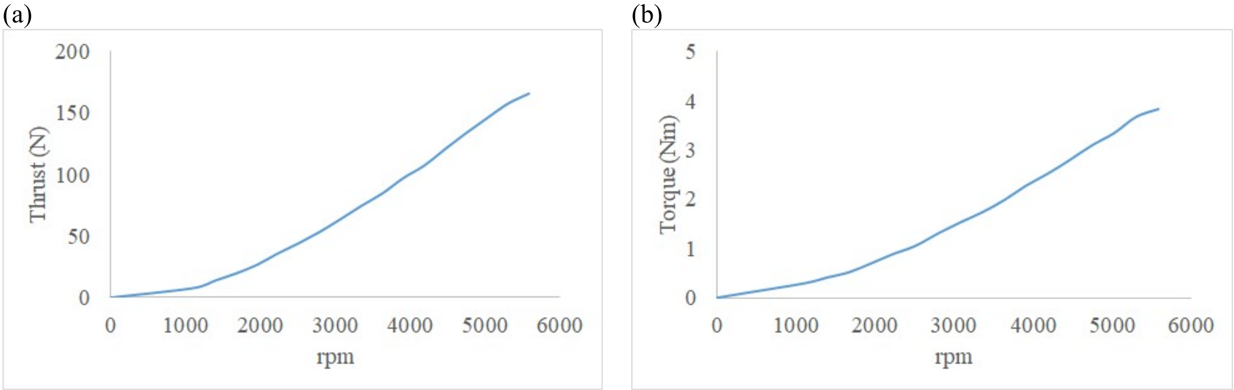

Fig. 4. Testing results of motor Q80-9M V2 with 27x8 propeller: a) Thrust versus revolute per minute, b) Torque versus revolute per minute.

5. Aerodynamic forces and moments

According to the procedures given in [5, 6, 7], following aerodynamic force and moment coefficients for horizontal flight mode are obtained:

-the lift coefficient

$$C_L = \left\{ \begin{array}{cc} 0.093159(\alpha + 1.6), & \alpha \le 8^\circ \\ -0.0008\alpha^3 + 0.0215\alpha^2 - 0.0964\alpha + 0.721, & 8^\circ < \alpha \le 14^0 \end{array} \right\} + 0.0058\delta_e + \\ +7.6135\frac{c_{ac}}{V}q + 1.5866\frac{c_{ac}}{V}\dot{\alpha}, \tag{14}$$

-the drag coefficient

$$C_D = -3.84 \cdot 10^{-6}\alpha^3 + 3.7172 \cdot 10^{-4}\alpha^2 + 0.00129296\alpha + 0.02721989 + 0.000117\delta_e, \tag{15}$$

-the side force coefficient

$$C_y = -0.00954\beta + 0.0022\delta_r + 0.0076\frac{b}{2V}p + 0.2928\frac{b}{2V}r - 0.045\frac{b}{2V}\dot{\beta}, \tag{16}$$

-the rolling moment coefficient

$$C_l = -0.00065\beta + 0.0042\delta_a + 9.21 \cdot 10^{-5}\delta_r - 0.434\frac{b}{2V}p + \\ + 0.0802\frac{b}{2V}r - 0.0008\frac{b}{2V}\dot{\beta}, \tag{17}$$

-the pitching moment coefficient

$$C_m = -0.0079 - 0.02833\alpha - 0.0271\delta_e - 17.1536\frac{c_{mac}}{V}q - 5.22\frac{c_{mac}}{V}\dot{\alpha}, \tag{18}$$

-and the yawing moment coefficient

$$C_{\mathrm{n}} = 0.002384\beta - 1.65 \cdot 10^{-4}\delta_{\mathrm{a}} - 9.58 \cdot 10^{-4}\delta_{\mathrm{r}} - 0.0306\frac{b}{2V}p + \\ - 0.1243\frac{b}{2V}r - 0.0182\frac{b}{2V}\dot{\beta}, \tag{19}$$

in which α and β present the angle of attack and the sideslip angle expressed in degrees respectively, δ_{a}, δ_{e} and δ_{r} are deflection angles of ailerons, elevator and rudders expressed in degrees respectively, p and r are the angular velocities about x and z axes expressed in rad/s respectively while c_{mac} presents the mean aerodynamics chord length. Rates of the angle of attack and the sideslip angle ($\dot{\alpha}$ and $\dot{\beta}$) are expressed in rad/s. Contributions of the propulsive force on aerodynamic force and moment coefficients are follows

$$C_{y\mathrm{T}} = -0.00025\beta,\ C_{m\mathrm{T}} = -0.00568\alpha,\ C_{n\mathrm{T}} = 2.967 \cdot 10^{-5}\beta. \tag{20}$$

These coefficients are implemented in mathematical model of the aircraft developed in “Simulink”. This simulation is intended to be first step for autopilot development.

6. Conclusion and future work

In this work, development of small electric fixed-wing VTOL UAV is presented. The developed vehicle has take-off weight 35 kg, can carry payloads up to 6 kg and it is fully electric. It has four fixed motors for its vertical propulsion, which are attached to the fixed wing platform making quad-copter configuration and a single motor for the horizontal propulsion. Beside vertical take-off and landing abilities, ALECS is also capable for conventionally take-off and landing if runway is present.

At this stage, the prototype of the ALECS is finished and exposed at the International Defense Exhibition and Conference (IDEX 2019) in Abu Dhabi (United Arab Emirates) (Fig. 5).

Fig. 5. ALECS VTOL exposed at the International Defense Exhibition and Conference (IDEX 2019) in Abu Dhabi (United Arab Emirates).

Future work is related to the autopilot system development, testing the aircraft in real flight and ground station development.

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