Bulgarian Academy of Sciences. Space Research and Technology Institute.
Aerospace Research in Bulgaria. 31, 2019, Sofia

DOI: https://doi.org/10.3897/arb.v31.e08

ELECTRIC VERTICAL TAKE-OFF AND LANDING FIXED WING UNMANNED AIRIAL VEHICLE FOR LONG ENDURANCE OR LONG RANGE?

Dimo Zafirov

Space Research and Technology Institute – Bulgarian Academy of Sciences
e-mail: zafirov@space.bas.bg

Keywords: *Long endurance, Long range, Joined wing, Ducted fan.*

Abstract

An analysis of requirements to electric vertical take-off and landing unmanned aerial vehicle with fixed wings is carried out in this article. These aircraft have to fulfil requirements of users and to be convenient for operation in any field conditions. Long flight duration and long flight range are important for most missions. Mathematical models for both cases are presented and it has been found that the requirements for the wing load are different.

It is recommended to use a type of UAV (Unmanned Aerial Vehicle) that is modular and allows performing flights with different configurations and payload depending on the mission in order to fulfil these requirements.

Notation

C_D – coefficient of drag force;

C_L – coefficient of lift force;

D – drag force of the aircraft;

E_{bat} – energy of the batteries;

$\overline{E_{bat}}$ – specific energy of the batteries;

F – thrust of the propulsions;

g – acceleration of gravity;

K – glade ratio;

K_e – glade ratio by maximum endurance;

K_R – glade ratio by maximum distance;

L – lift force of the aircraft;

m_0 – take-off mass;

m_p – mass of the payload;

m_{bat} – mass of the batteries;

m_{empty} – empty mass of the aircraft;

$\overline{m_{bat}}$ – specific mass of the batteries;

$\overline{m_p}$ – specific mass of the payload;

$\overline{m_{empty}}$ – specific mass of the empty aircraft;

P – power;

R – distance of the flight;

S – wing area;

t – flight time;

t_e – endurance time;

V – air speed of the aircraft;

V_c – cruise speed of the aircraft;

W_0 – take-off weight;

ρ – air density.

1. State of the Arts

The number of UAV has been increasing exponentially because of a large number of applications where they can be used. Different types of configurations, propulsors, sources of energy, and payloads have been used.

Different UAV, that perform vertical take-off and landing, have appeared recently. Most of them are multi-rotary UAV (copters) that are suitable for mission where stationary hanging or target tracking are required. These UAV possess low energy efficiency due to their low glade ratio ($K \approx 1$) that defines relatively short endurance. In addition, they cannot be used with strong wind.

Fixed wing UAVs possess better glare ratio and flight duration. However, they need even runways for take-off and landing and these aircraft are not capable to perform motionless hovering flight.

In this respect, designers have been working persistently on a combination of fixed wing aircraft and copter in order to achieve their advantages. In many cases, these UAV do not possess good weighting perfection because they are powered with different propulsors for vertical and horizontal flight. This increases their empty weight.

Electrical UAVs are favourites in terms of convenience in maintenance. These aircraft can be prepared for flight quickly and they possess a high level of airworthiness.

The article discusses the possibility for development of VTOL e-UAV that is convenient in maintenance. The aircraft will be able to take off and land vertically, and will be able to perform a motionless hovering flight. In addition, e-UAV will possess long endurance and long range.

2. Initial Requirements

Marketing analyses shows that customers would like to have UAV that possess long endurance or long range, vertical take-off and landing, vehicles that are able to perform motionless hovering flight, aircraft that are capable to localize and follow targets, or perform scanning of large areas. Payload mass of cameras and other equipment, all together with the gimbals, is less than 2 (two) kilograms. Customers require a high level of reliability and simple maintenance and flight operations.

Customers have different requirements according to flight missions. Long endurance is required with missions for radio signal retranslation or monitoring of small areas.

Long range is required with mission for:

- Surveying and Mapping;
- Precision Agriculture;
- Search and Rescue;
- Security;
- Logistics.

Some customers admit that this means maximum distance between UAV and GCS with sustainable receiving of video-information and transmission of control signals. Meanwhile, long range is required for most missions (for example – scanning).

Customers often look for long endurance UAVs for missions where scanning of large areas and remote objects are carried out and UAVs fly a great distance. With aircraft that perform horizontal take-off and landing, speeds providing long endurance and long range are almost equal so that the requirements are fulfilled by the same aircraft.

3. Requirements

Let us look at separate subsystems of Unmanned Aviation System (UAS) that fulfils customer requirements completely.

3.1. The structure

Aerodynamic and weight efficiency is defined by the aircraft configuration. One of possible configurations is the scheme Joined Wing that provides a great level of lift [1] and produces a low level of drag. Joined Wing scheme possesses high weight efficiency due to a high level of frame strength that the wing creates and due to the absence of landing gear.

The scheme provides the possibility for vertical take-off and landing of UAV only through a simple rotation of one or several propulsors. In this case, the thrust always has to pass through the centre of gravity of the aircraft. (Fig. 1).

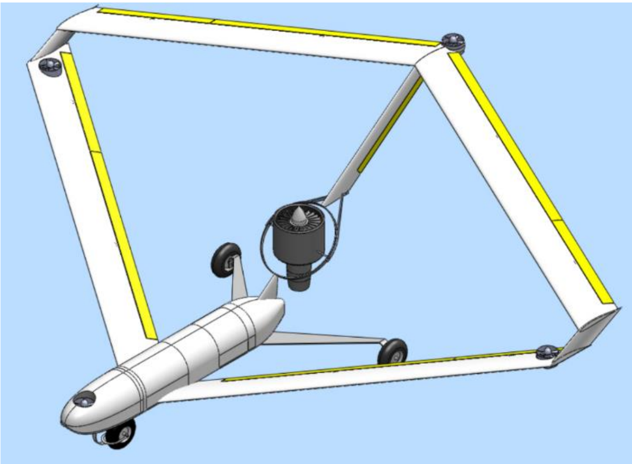

Fig. 1. UAV "Joined Wing" Configuration

3.2. Propulsors

Propellers, ducted fans, and jet engines are used for thrust (moving power) creation on UAV. A small number of military UAV are powered by jet engines. Marketing researches [2] show that a large number of UAV will be used for civilian applications. These aircraft are powered by air propellers or ducted fans.

Propellers for VTOL UAV possess great dimensions and they are inefficient during a horizontal flight. Aircraft that are powered by one type of propulsors for vertical flight and hanging and other type for horizontal flight have been used recently. However, this scheme makes their usage inefficient in a weighting aspect.

Ducted fans are used more frequently in comparison with air propellers due to their smaller dimensions at equal thrust. They work effectively during take-off, landing and at cruise velocity [3] Fig. 2.

Fig. 2. Ducted Fan Propulsor

In addition, ducted fans are effective during horizontal and vertical flight and also for control that improve the thrust efficiency of the aircraft.

3.3. Energy sources

Electric batteries are the most suitable source of energy for UAV and 96 % of UAV are electrical at the moment. Batteries have been developed very quickly and the specific energy of the new models has increased recently. NASA forecast [4] shows that the specific energy is expected to reach 1.200 Wh/kg in 2026 by going up more than four times. Specific energy is a basic feature of the electric battery defining flight endurance and range of UAV.

3.4. Electric motors

Electric motors that are made of neodymium alloys such as N50 and N52 possess a great specific power. Some electric motors, produced by SIEMENS, reach a specific power of 6 kW/kg that provide good thrust efficiency for UAV. In addition, revolutions of the motor can be controlled quickly and properly.

4. Basic features of e-VTOL UAV

Basic features of e-VTOL UAV are defined at the following flight modes (mission elements):

- Take-off;
- Climbing;
- Horizontal flight;

  - Long endurance;
  - Long range;
- Hovering flight;
- Descending;
- Landing.

Gimbals with mounted payload at weight of 2 kg are the most commonly used. We also place requirements e-VTOL UAV in development to possess maximum endurance or maximum range. These features can be achieved when the battery weight is maximum.

EASA standards for specific missions carried out by UAV require the take-off weight of aircraft not to exceed 25 kg. It is a limit value. When the take-off weight is more than 25 kg, UAV will belong to a certified category of UAV with higher requirements and expensive procedures of certification. Then:

(1) $$m_o = m_p + m_{bat} + m_{empty} \; [kg];$$

(2) $$1 = \frac{m_p + m_{bat} + m_{empty}}{m_0};$$

(3) $$\overline{m_{bat}} = 1 - \overline{m_{empty}} - \overline{m_{p}}.$$

The empty weight of UAV depends on many characteristics of the aircraft, materials and components [5–7]. In order to achieve a maximum value for t_e *or* R, m_{empty} has to be minimum.

Take-off mode, landing mode, and ascending mode will be short-term. The main part of the energy will be used for the horizontal flight – to achieve a maximum endurance t_e , or a maximum range R.

Maximum values for t_e *or* R depend on the amount of energy that can be provided by the batteries:

(4) $$E_{bat} = \overline{E_{bat}} m_{bat} \; [Wh],$$

where $\overline{E_{bat}}$ *[Wh/kg]* is the specific energy of the battery.

At the moment, the maximum value of specific energy of $\overline{E_{bat}} \approx 300$ Wh/kg is provided by batteries based on lithium. It is expected that they will be leaders in the future and their specific energy will reach a value of 1.200 Wh/kg until 2026.

In a horizontal flight of electric planes, following formulas are applicable:

(5) $$L = W_0 = C_L S \frac{\rho V^2}{2} \; [N]$$

(6) $F = D = C_D S \frac{\rho V^2}{2}\ [N]$

(7) $K = \frac{L}{D} = \frac{W_0}{F} = \frac{C_L}{C_D}$

(8) $F = \frac{W_0}{K} = \frac{m_0 g}{K}\ [N]$

(9) $P = FV\ [W]$

(10) $E = Pt = FVt = FR\ [Wh].$

4.1. Maximum endurance

For maximum endurance mode of flight:

(11) $L_e = W_0 = m_0 g = C_L S \frac{\rho V_e^2}{2}\ [N]$

(12) $F_e = D_e = C_D S \frac{\rho V_e^2}{2}\ [N]$

(13) $K_e = \frac{L_e}{D_e} = \frac{W_e}{F_e} = \frac{C_{L_e}}{C_{D_e}}.$

Maximum endurance mode is achieved when the ratio ${C_L^3}/{C_D^2}$ is maximum and:

(14) $P_e = \frac{F_e V_e}{\eta}\ [W]$

(15) $F_e = \frac{m_0 g}{K_e}\ [N]$

(16) $V_e = \sqrt[2]{\frac{2L}{\rho C_{L_e} S}} = \sqrt[2]{\frac{2 m_0 g}{\rho C_{L_e} S}} = \sqrt[2]{\frac{2 g p_0}{\rho C_{L_e}}}\ [m/s]$

(17) $E_A = P_e t = F_e V_e t = \frac{m_0 g}{K_e} R\ [Wh)$

(18) $t_e = \frac{E_A}{P_e} = \eta \frac{\bar{E}_A m_{bat}}{F_e V_e} = \eta \frac{\bar{E}_A m_{bat}}{\frac{m_0 g}{K_e} V_e} = \eta \frac{\bar{E}_A \overline{m_{bat}} K_e}{g V_e}\ [s].$

A maximum flight time can be achieved at a maximal value of the ratio $\frac{\overline{m_{bat}}}{V_e}$, that is reached at $p_{0_{opt}}$. When increasing p_0, V_e also increases so that the ratio quickly decreases. The maximum value will probably be achieved at a low speed V_e.

In order to accomplish a maximum flight time (endurance), UAV need to possess maximum energy E_A and respectively weight of the battery m_{bat}, highly effective propulsors with thrust F_e and UAV with a maximum glade ratio K_e at maximum value of the ratio C_L^3/C_D^2.

4.2. Maximum range

A maximum range is achieved when the glade ratio K_R is maximum and:

(19) $$E_A = P_R t \ [Wh]$$

(20) $$R = V_c t = V_c \frac{E_A}{P_R} = V_c \frac{E_{RA}}{F_R V_c} = \frac{\bar{E}_A m_{bat}}{F_R} = \frac{\bar{E}_A \overline{m_{bat}} m_0}{F_R} = \frac{\bar{E}_A \overline{m_{bat}} m_0}{\frac{m_O g}{K_R}} = \frac{\bar{E}_A \overline{m_{bat}} K_R}{g} \ [m].$$

The maximum range will be as high as the available energy $\bar{E}_A \overline{m_{bat}}$ and the glider ratio by cruise speed K_R are higher. For one aircraft, the higher the cruise speed V_c is, the shorter the flight time t is, and vice versa. When developing e-VTOL UAV, engineers can select a higher value of wing load p_0 and respectively a smaller wing area. In this case, a lower value of empty mass and respectively a higher value of the cruise speed can be achieved. When accepted that m_0= 25 kg, the battery weight and therefore the flight range can be increased. The maximum value of p_0 can be determined by structure considerations and payload limits.

When developing e-VTOL UAV with a long range, we have to accomplish the highest glade ratio and select a high value of the wing load p_0 that is much higher than at horizontally take-off and landing UAVs. Meanwhile, maximum $\overline{m_{empty}}$ can be achieved by using non-standard balancing scheme, for example "Joined wing" configuration. In most missions of e-VTOLUAV, a higher cruise speed means a higher productivity.

Conclusion

The maximum endurance of flight can be achieved at a low value of the maximum endurance speed V_e and respectively at a low value of p_0. While maximum range of flight can be achieved at a high cruise speed V_c and respectively at a high value of p_0.

It is difficult to reach an acceptable compromise in the presence of such contradictory requirements for the wing load for both modes of flight of e-VTOL UAV. A good solution can be achieved by using a module configuration and wing systems with a different wing load.

Acknowledgements

Set up under the project 9иф-02-4/28.11.2018 “Development of an innovative drone with long endurance and high altitude”, financed by the National Innovation Fund of Ministry of Economic of Republic of Bulgaria.

References

1. Zafirov, D. Joined Wings Thrust Vectored UAV Flight Envelope, AIAA Atmospheric Flight Mechanic Conference, 2010, Toronto, Ontario, Canada, 2–5 August 2010, Volume 1, Curran Associates, Inc., pp. 153–61, ISBN:978-1-61782-333-6.
2. Unmanned Aerial Vehicles Market – Growth, Trends, And Forecast (2019–2024). 2018, Mordor Intelligence, URL: https://www.mordorintelligence.com/industry-reports/uav-market
3. Zafirov, D. and H. Panajotov, UAV Joined-Wing Test Bed. In: Proceedings of 4th CEAS in Linköping, 2013, Sweden, pp. 516–524, mISBN 978-91-7519-519-3.
4. https://nari.arc.nasa.gov/sites/default/files/attachments/TVF_Roadmap_v5.2.xlsx.
5. Stojkov, O. and I. Kamburov. Matematicheski model na eksploataciJata na sistemite za upravlenie na aviacionnoto v"or"zhenie, Nauchni trudove “VNVVU G. Benkovski”, 1983, No. 44, Military Publishing House, Sofia. (in Bulgarian)
6. Stojkov, O. Kompleksna obrabotka na informacijata poluchavana ot razlichni datchici. Nauchni trudove “VNVVU G. Benkovski”, 1988, No. 51. (in Bulgarian)
7. Stojkov, O. Optiko elektronni sistemi. NVU “V. Levski”, fakultet “Aviacionen”, Jubilejna nauchna sesija, 2005, Vol. 1, D. Mitropolija, pp. 164–170, ISBN 954-713-071-4 (in Bulgarian)

ЕЛЕКТРИЧЕСКИ ВЕРТИКАЛНО ИЗЛИТАЩ И КАЦАЩ БЕЗПИЛОТЕН САМОЛЕТ ЗА ГОЛЯМА ПРОДЪЛЖИТЕЛНОСТ И ДАЛЕЧИНА НА ПОЛЕТА?

Д. Зафиров

Резюме

В статията се прави анализ на изискванията към вертикално излитащи и кацащи електрически безпилотни самолети, които да отговарят на изискванията на потребителите и са удобни за експлоатация при всякакви теренни условия. За много от изпълняваните мисии е важно да се осигури голяма продължителност на полета или голямо изминато разстояние. Разгледани са математически модели за двата случая и е установено, че изискванията за крилното натоварване са различни. За да се изпълнят те, се препоръча използването на вариант на безпилотен самолет, който да е модулен и да позволява използването на различни конфигурации и полезни товари, в зависимост от мисията, която ще се изпълнява.