LIGHT eVTOL POSSIBLE AERODYNAMIC CONFIGURATIONS ANALYSIS

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Abstract

The present study endeavors to consider the most popular eVTOL aerodynamic concepts employed nowadays. This research gives a theoretical evaluation of the possible VTOL design with different electric or hybrid power plant configurations. Conventional rotorcraft, quadcopter with ducted fans or just rotors have been considered. Relationship between eVTOL mass parameters and available power of the power plant is calculated. Performance of the VTOL with full electric and different hybrid power plants in forward flight mode is estimated. Available and required power needs for speed envelope in hover and maximal speed modes are calculated. Optimal specific parameters (batteries, generators, electric motors) of fully electric and hybrid power plant elements are defined to provide acceptable eVTOL flight performance.

1. INTRODUCTION

The forecast analysis reveals that urban traffic has to become more complicated for the next few years and the number of megalopolises is growing up. At the same time the quality of life in such areas is expected to continually degrade. As a result, the necessity arose to dramatically decrease traffic overloading and to minimize environmental pollution. It appears the brand new mobile concept including absolutely new background and new traffic idea that presumes both upgraded infrastructure and new mobile approach.

Today, one of the most promising ways of air vehicle evolution is an eVTOL (electric Vertical Take-Off and Landing) concept. Electrically driven VTOL features higher efficiency, environmental security and cheaper life cycle expenses.

New eVTOL design needs to be globally reconsidered in terms of VTOL main systems architecture.

This enthusiasm is stimulated on one hand by automobile electric engine evolution (and recently applied in aviation as well) and on the other hand by increasing number of the ground traffic problems induced by growing number of ground vehicles.

Development and improvement of the small unmanned aerial vehicles (SUAV) equipped mainly with electric power engines has become perceivable impulse to eVTOL evolution.

Essential difference in power efficiency of conventional hydrocarbon fuel and electrochemical battery (12000 W·h/kg versus 150-200 W·h/kg) forces eVTOL designers to foresee many different aerodynamic solutions in order to minimize power consumption. That makes understandable extremely wide variety of eVTOL concepts and designs.

The present study makes an attempt to consider the key features of the most popular aerodynamic configurations of our days. In general, it says about multirotor configurations, i.e. application of several electrically driven rotors in different combinations like single or coaxial rotors or ducted fans. It should be emphasized that we witness an emergence of the newly-born type of VTOL which is

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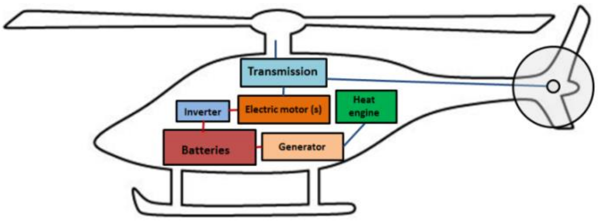
fundamentally discrepant of conventional helicopter. Such new VTOLs do not require sophisticated transmission gear to reduce combustion or gas turbine engine 5000-20000 rpm to 300-400 rpm of the rotor resulting in torque reduction – new VTOLs came up with the idea of rotor installation just on the electromotor output shaft. Also, swashplate is no more required – eVTOL alternates forces and torques by simple changing electromotor rpm or collective pitch. Thus, there is no need in hydraulic servos and hydraulic system any more.

The present research also gives a theoretical evaluation of the possible VTOL design with fully electric and hybrid power plant configurations that are comparable to the light helicopter class like Mi-34 (Fig. 1). Conventional rotorcraft, quadcopter with ducted fans or just rotors have been considered. Flight performance of the eVTOL with full electric and hybrid power plants are estimated. Dependences of the required power of eVTOL on flight speed are calculated. The proceeding demonstrates influence of power plant components (batteries, generators, electric motors, inverters, etc.) specific parameters on eVTOL flight performance.

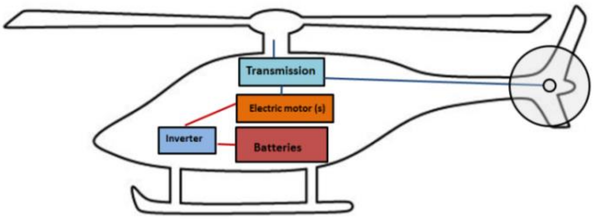
Figure 1. Mi-34C helicopter

There have been provided calculations for the following VTOL configurations:

- conventional helicopter with one main rotor and one tail rotor. This configuration included design with electrically driven main rotor and tail rotor with mechanical transmission (Fig. 2);
- quadcopter with 4 X-type rotors (Fig. 3);
- quadcopter with 4 X-type ducted fans (Fig. 4).



a



b

Figure 2. Basic elements of a single-rotor helicopter power plant. Hybrid (a) fully electric (b) power plant

Each eVTOL configuration calculation is done for fully electric and hybrid power plant. For the flight safety reason in case of the engine failure quadcopter must ensure that each rotor-engine couple should be duplicated by means of coaxial rotors application. The reason is that aircraft with a single rotor-engine couple cannot be trimmed in steady flight in case of one engine failure. The other safety reason assurance might be application of synchronized shafts between engines; however, this one requires collective pitch control which makes such design more complicated.

Flight performance of the above VTOL configurations was estimated in order to compare their efficiency. All calculations based on momentum theory methods accepted possible adjustments depending on outcome of experiment. There was considered rotorcraft with fixed payload. For each of its configurations such parameters as required power in hover mode, approximate aircraft construction and power plant masses were evaluated. Provided that only batteries were used, potential endurance was estimated. In some cases hybrid power plant possible implementation along with flight range were compared.

Obtained results might be taken as the first approximation for the further studies related with the new eVTOL concept exploring.

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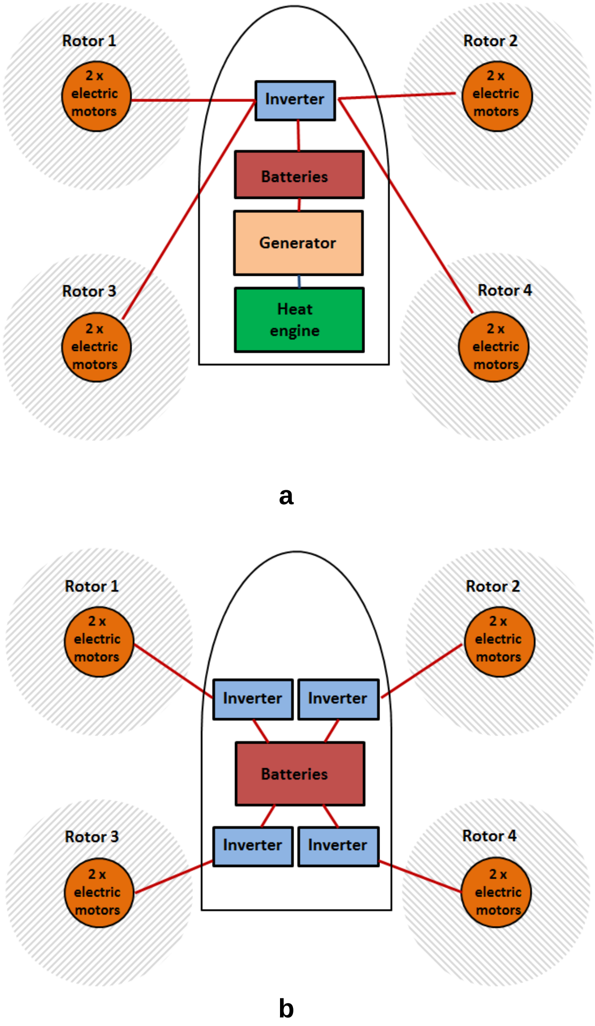

Figure 3. The power plant elements of the open-rotor quadcopter. Hybrid (a) and full-electric (b) power plant

2. MATHEMATICAL MODEL OF THE eVTOL CONCEPT WITH HYBRID OR FULL ELECTRIC POWER PLANT

Mathematical model of the eVTOL concept is based on flight vehicle existence equation as follows:

(1) $$m_0(1-\bar{m}_{rs}-\bar{m}_a-\bar{m}_{ue}-\bar{m}_{ae}-\bar{m}_{ew}) = Nn_{MR}k_p\left(\frac{1}{\bar{N}_{EM}}+\frac{1}{\bar{N}_{gen}}+\frac{1}{\bar{N}_{HE}}+\bar{m}_{inv}\right)+\bar{m}_{bat}Nn_{MR}t_{end}+m_f+m_{trans}+m_{FC}+m_{FS}+m_{OS}+m_{Ch}+m_{PL}+m_{cr}+m_{TR},$$

where N – thrust engine power in hover mode, $k_p \geq 1$ – power plant safety factor, $m_{\rm PL}$ – mass of the payload, m_{cr} – crew personnel mass, t_{end} – battery electric thrust hovering endurance, $m_{\rm FV}$ – flight vehicle mass, $\bar{N}_{HE}$ – heat engine (ICE or GTE) specific power, n_{MR} – number of main rotors.

Equation (1) is universal for all types of eVTOL considering in the study, with both full electric and hybrid power plant. In general, equation (1) is nonlinear as relating to *N* and its solution can be obtained only by numerical technique.

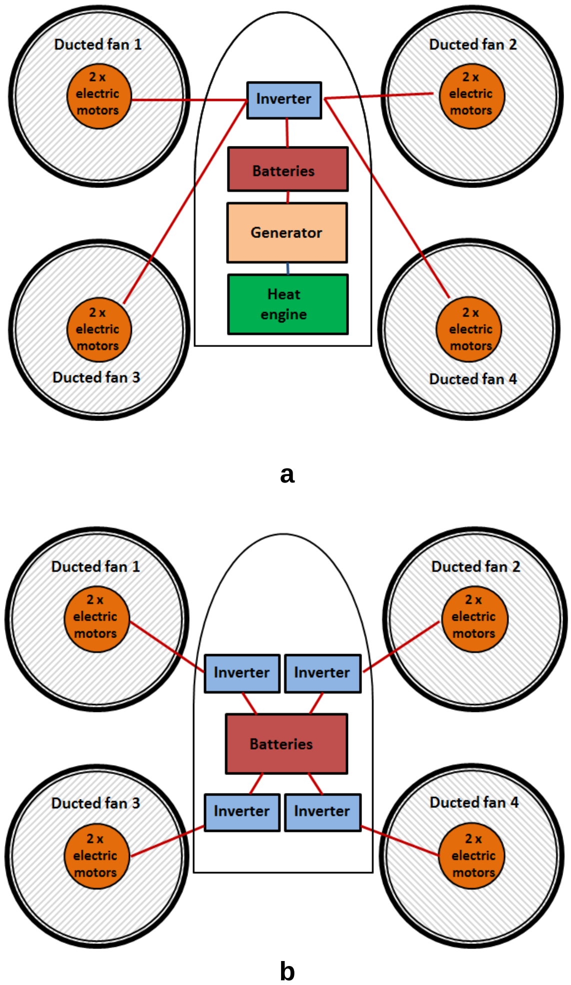

Figure 4. The power plant elements of the quadcopter with ducted fans. Hybrid (a) and full-electric (b) power plant

2.1. Aerodynamic prediction for multirotor eVTOL with open rotors and conventional single-rotor helicopter

According to the momentum theory open rotor thrust in hover mode can be evaluated with the reasonable for an initial estimate accuracy [1, 2]

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(2) $$T = (2\rho F_{MR} N^2)^{1/3},$$

where ρ – air density, $F_{MR} = 0.25\pi D_{MR}^2$ – rotor disk area, D_{MR} – main rotor diameter, N –electric motor thrust power.

Rearranging expression (2) and taking into account coefficients η, ξ and χ we will get the following:

(3) $$T = \left(N\xi\eta\sqrt{2\rho F_{MR}\chi}\right)^{2/3},$$

where ξ– mechanical transmission loss factor due to cooling and torque compensation, η – main rotor efficiency factor equals to ratio of working power required for flight vehicle in hover mode to consumed work, N – power plant output, χ – ratio of the effective rotor disk area contributing to thrust generation to the total disk area F_{MR} .

Equating formula (3) to the flight vehicle weight $T = G = m_0 g$, we'll get the flight vehicle mass expression:

(4) $$m_0 = \frac{1}{g}\left(N\xi\eta\sqrt{2\rho F_{MR}\chi}\right)^{2/3},$$

where g – gravitational acceleration.

Substituting expression (4) in equation (1) we get nonlinear equation relating to N for the hover mode.

(5) $$\frac{n_{MR}}{g}\left(N\xi\eta\sqrt{2\rho F_{MR}\chi}\right)^{2/3}(1 - \bar{m}_{rs} - \bar{m}_a - \bar{m}_{ue} - \bar{m}_{ae} - \bar{m}_{ew}) - N n_{MR} k_p \left(\frac{1}{\bar{N}_{EM}} - \frac{1}{\bar{N}_{gen}} - \frac{1}{\bar{N}_{HE}} - \bar{m}_{inv}\right) - \bar{m}_{bat} N n_{MR} t_{end} - m_f - m_{trans} - m_{FC} - m_{fs} - m_{os} - m_{Ch} - m_{PL} - m_{cr} - m_{TR} = 0.$$

Analytic solution of the equation (5) is too intricate, therefore numerical solution has been found.

To calculate the induced power of the free rotor in sidewise rotor flow mode we used the Glauert theory [1,2]. It was assumed that the main rotor had the rotor flow with velocity V and the angle of attack α.

Let us introduce velocity normalized components – parallel and normal to rotor disk. These components are called rotor performance coefficient μ and inflow ratio λ respectively, and they are defined by the following formulae

(6) $$\mu = \frac{V\cos\alpha}{\Omega R},\ \lambda = \frac{V\sin\alpha + v}{\Omega R} = \mu\tan\alpha + \lambda_i,$$

where induced velocity presented as induced inflow ratio

(7) $$\lambda_i = \frac{C_T}{2\sqrt{\mu^2+\lambda^2}}.$$

Inflow ratio λ can be found from the solution of the equation

(8) $$\lambda - \mu\tan\alpha - C_T/\left(2\sqrt{\mu^2+\lambda^2}\right) = 0$$

For each rotor, thrust coefficient C_T is defined by the formula

(9) $$C_T = \frac{T}{\rho F_{MR}(\Omega R)^2}\ .$$

Main rotor thrust in (9) can be calculated as follows

(10) $$T = G/(n_{MR}\cos\alpha).$$

Formula (10) is fair for any type of VTOL with open rotors on the assumption with the rotor angle of attack absolute value approximately equals to the pitch trim angle. Such an assumption is true in case of the disk plane parallels plane of cross-section of flight vehicle. Also, we have to assume that each rotor thrust of the multirotor VTOL is the same. For example, such an assumption would not be correct for tandem helicopter with overlapped rotors and mutual interference strong enough. However, in case of light VTOL with offset rotors without overlapping or ducted fans it is admissible for provisional estimate.

Power, required for VTOL cruise flight can be represented in the sum of induced power, blade profile drag power and shock wave power as well as parasite non-structural drag:

(11) $$P = P_i + P_0 + P_w + P_p$$

or going to power factors

(12) $$C_P = C_{Pi} + C_{P_0} + C_{P_w} + C_{P_p}$$

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Coeffs in (12) might be calculated as following:

(13) $$C_{Pi} = P_i/\rho F_{MR}(\Omega R)^3 = Tv/\rho F_{\mathrm{MR}}(\Omega R)^3$$

(14) $$C_{P_0} = \sigma c_{d_0}(1 + 4.6\mu^2)/8$$

(15) $$C_{P_w} \approx K_c(M_0 - 0.4)^2,$$

where K_c – compressibility factor, depending on aerodynamic configuration, geometric twist and blades finishing, main rotor thrust coefficient and VTOL velocity

(16) $$C_{P_p} = DV/\rho F_{MR}(\Omega R)^3$$

Then required power *P* will be defined as follows:

(17) $$P = C_P \rho F_{MR}(\Omega R)^3.$$

Consequently, required rotor mast torque may be evaluated as following

(18) $$M = P/\Omega$$

2.2. Aerodynamic prediction for multirotor eVTOL with ducted fans

We used momentum theory to calculate ducted fan thrust as well [3]. According to the momentum theory ducted fan thrust may be represented in the sum of rotor thrust and duct thrust form (Figure 5).

(19) $$T = T_D + T_R$$

Expression (19) is handier to use in dimensionless form relative to summarized ducted fan thrust T

(20) $$\overline{T}_D + \overline{T}_R = 1$$

Summarized ducted fan thrust in ground running operation mode might be calculated as follows

(21) $$T = K\left(\sqrt{2\rho\pi R^2}\eta_0 P\right)^{2/3},$$

where K – quality index of the "ducted fan system"

(22) $$K = \sqrt[3]{k_V/2\overline{T}_{D0}^2},$$

(23) $$k_V = V_2/V_1 = 1/n,$$

(24) $$n = \left(1 + \overline{H}_D \tan\frac{\alpha_D}{2}\right)^2$$

(25) $$\overline{T}_{D0} = \frac{1}{2k_V}(k_V^2 + \xi_k)$$

n – diffuser area ratio, $V_1 = V + v_1$ – inflow rate in rotor disk plane, $V_2 = V + v_2$ – total velocity in outgoing flow, V – undisturbed velocity, ξ_k– aggregate coefficient of local drag, P – ducted fan required power in ground running operation mode

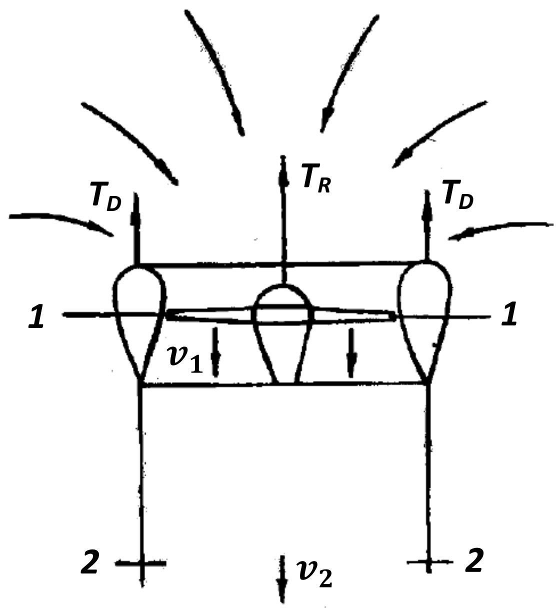

Figure 5. Ducted fan in ground running operation mode [3]

(26) $$\xi_k = \xi_c + \xi_d + \xi_o$$

ξ_c – duct inlet loss (contracting duct), ξ_d – diffusor loss, ξ_o – other internals loss.

For the ducted fan thrust calculation in axial flow mode we might assume that undisturbed ram air runs towards ducted fan axis with velocity V.

Expression for the relative ducted fan thrust might be represented as following [3]:

(27) $$\overline{T}_R = \frac{\overline{T}_{D0} - \frac{\hat{V}}{2k_V}\left[\xi_c(2-\hat{V}) + k_V^2\hat{V}\right]}{1-\hat{V}},$$

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where $\overline{T}_{R0}$ – relative thrust in ground running operation mode,

(28) $$\hat{V} = 2/\left(1+\sqrt{1+\frac{4Tk_V}{\rho F_{MR}V^2}}\right).$$

Table 1. Initial data for eVTOL with fully electric power plant performance prediction

Specification	*Conventional Rotorcraft*	*Quadcopter with open rotors*	*Quadcopter with ducted fans*
n_{MR}	1	4	4
D_{MR}	10	3	3
η	0,7	0,85	0,9
χ	0,95	0,95	0,95
ξ	0,85	1	1
$\overline{N}_{EM}$, kW·h/kg	5	5	5
$\overline{N}_{GEN}$, kW/kg	5	5	5
$\overline{m}_{bat}$, kg/kW·h	4	4	4
$\overline{m}_{inv}$, kg/kW	0,1	0,1	0,1
m_{PL},kg	210	210	210

Input ducted fan power would be defined as fan power consumption:

(29) $$P = T_R V_1,$$

where V_1 – inflow rate in rotor disk plane.

Let us introduce dimensionless velocity $\tilde{V}_1 = V_1/v_{10}$, where $v_{10} = \sqrt{T/\rho k_V F_{MR}}$ – rate of flow through disk area in ground running operation mode.

In case of axial flow, expression for $\tilde{V}_1$ can be obtained using momentum equation to airflow ingoing along an axis of the ducted fan.

(30) $$T = m(V_2 - V) = m(k_V V_1 - V);$$
$$m = \rho F_{MR} V_1 = \rho F_{MR} V_2/k_V$$

Evaluating V_1 from (29) and relating all velocities to v_{10} we'll get:

(31) $$\tilde{V}_1 = \left(\tilde{V} + \sqrt{\tilde{V}^2 + 4k_V^2}\right)/2k_V$$

As it was shown in [3] all formulae, we have taken above, can be used in case of sidewise flow. Such a mode is typical for VTOL having rotor system by means of ducted fans fixed relative to flight vehicle airframe in cruise flight mode and during climb with slant path. For tilt rotors sidewise flow is typical in transitional flight.

Therefore, aerodynamic prediction of the ducted fan in sidewise mode is similar to that of the axial flow mode with specific velocity component $V_y = V\sin\alpha.$ However, it should be noted that application of the above algorithm for a sidewise flow mode is admissible if the duct length is quite enough for the airflow flowing through the fan to lose completely its horizontal component and diffusor output flow is in the form of fully expanded axial flow with free-stream pressure ratio equals to atmospheric one.

3. eVTOL AERODYNAMIC CONFIGURATION PREDICTED RESULTS

Initial data for eVTOL performance prediction with fully electric power plant and hybrid power plant are represented in Table 1 and Table 2 respectively.

Specific mass parameters for thrust electric motors, generators, batteries, inverters, diesel and gas turbine power plants available presently were chosen based on information provided by open sources and papers [4, 5].

Performance prediction was done for the three types of power plant: 1) hybrid power plant with heat engine and batteries allowing hovering for 5 min, 2) fully electric power plant. The reason of the diesel engine application in hybrid power plant is due to its best fuel consumption efficiency among other types of internal combustion engines. eVTOL structural elements mass distribution resulting from aerodynamic prediction related to take-off mass of different types of power plants is represented in Tables 3, 4. Mass distributions in absolute values (kg) for all considering eVTOL are shown on Figure 6-11.

Functionality obtained shows that the main contribution to the flight vehicle mass with hybrid power plant comes from the fuselage structure mass components and internal combustion engine. Moreover, for a single rotor helicopter fuselage structure mass contribution prevails.

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This can be explained by less required power that helicopter power plant employs in comparison with quadcopters.

Table 2. Initial data for eVTOL with hybrid power plant performance prediction

Specification	*Conventional Rotorcraft*	*Quadcopter with open rotors*	*Quadcopter with ducted fans*
n_{MR}	1	4	4
D_{MR}	10	3	3
η	0,7	0,86	0,91
χ	0,95	0,95	0,95
ξ	0,85	1	1
C_e, kg/kW·h	0,3	0,3	0,3
$\bar{N}_{EM}$, kW/kg	5	5	5
$\bar{N}_{gen}$, kW/kg	5	5	5
$\bar{m}_{bat}$, kg/kW·h	4	4	4
$\bar{m}_{inv}$, kg/kW	0,1	0,1	0,1
$\bar{N}_{ICE}$, kW/kg	1,3	1,3	1,3
m_{PL}, kg	210	210	210

Table 3. eVTOL with fully electric power plant predictions

Specification	*Conventional Rotorcraft*	*Quadcopter with open rotors*	*Quadcopter with ducted fans*
$\bar{m}_{bat}$	0,2851	0,3844	0,3948
$\bar{m}_{rs}$	0,0764	0,0721	0,0775
$\bar{m}_{a}$	0,1566	0,1253	0,1253
m_{PL}/m_0	0,1174	0,0924	0,0859
$\bar{m}_{cr}$	0,0895	0,0704	0,0654
$\bar{m}_{ae}$	0,0683	0,0537	0,0499
$\bar{m}_{inv}$	0,0163	0,0219	0,0225
$\bar{m}_{EM}$	0,0325	0,0876	0,0900
$\bar{m}_{FC}$	0,0343	0,0270	0,0251
$\bar{m}_{ew}$	0,0400	0,0400	0,0400
$\bar{m}_{ue}$	0,0177	0,0139	0,0129
$\bar{m}_{Ch}$	0,0144	0,0113	0,0105
$\bar{m}_{trans}$	0,0486	0,0000	0,0000
$\bar{m}_{TR}$	0,0030	0,0000	0,0000
m_0, kg	1788	2274	2446

Table 4. eVTOL with hybrid power plant predictions

Specification	*Conventional Rotorcraft*	*Quadcopter with open rotors*	*Quadcopter with ducted fans*
$\bar{m}_{ICE}$	0,1466	0,1830	0,1933
$\bar{m}_{a}$	0,1566	0,1253	0,1253
m_{PL}/m_0	0,1058	0,0946	0,0872
$\bar{m}_{rs}$	0,0688	0,0739	0,0788
$\bar{m}_{cr}$	0,0806	0,0721	0,0665
$\bar{m}_{bat}$	0,0573	0,0715	0,0756
$\bar{m}_{inv}$	0,0172	0,0215	0,0227
$\bar{m}_{f}$	0,0660	0,0590	0,0544
$\bar{m}_{ae}$	0,0615	0,0550	0,0507
$\bar{m}_{EM}$	0,0344	0,0859	0,0907
$\bar{m}_{gen}$	0,0344	0,0429	0,0454
$\bar{m}_{FC}$	0,0309	0,0277	0,0255
$\bar{m}_{ew}$	0,0400	0,0400	0,0400
$\bar{m}_{ae.}$	0,0160	0,0143	0,0131
$\bar{m}_{fs}$	0,0147	0,0132	0,0121
$\bar{m}_{Ch}$	0,0130	0,0116	0,0107
$\bar{m}_{os}$	0,0096	0,0086	0,0079
$\bar{m}_{trans}$	0,0438	0,0000	0,0000
$\bar{m}_{TR}$	0,0027	0,0000	0,0000
m_0, kg	1984	2219	2407

In case of fully electric power plant the main contribution to the different flight vehicle mass comes from batteries. Their mass reaches 28,5 % of MTOW for a single rotor helicopter. Maximal mass contribution of 39,5 % to the vehicle mass comes from batteries of the ducted fan quadcopter. In case of open rotors quadcopter it reaches 38,4%. Single rotor helicopter with both types of power plant has obvious load factor advantage (10,6 – 11,7%). The least load factor value belongs to quadcopter with ducted fans (8,6 – 8,7 %).

Having done structure elements mass distribution computation we did analytical prediction of the flight vehicle general performance.

Hybrid power plant eVTOL flight range and endurance is defined by fuel range that can be defined by formulae (32), (33), employed for the flight vehicle with conventional power plant performance calculation.

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(32) $$L = \int_{m_1}^{m_0} \frac{dm}{q_r},$$

(33) $$t = \int_{m_1}^{m_0} \frac{dm}{q_h},$$

where m_0 and m_1 – eVTOL mass in the beginning and at the end of the level-flight segment for which computation is done. If cargo is not dropped, eVTOL mass change equals to fuel consumption at level-flight leg:

(34) $$m_f = m_0 - m_1$$

Hourly and range fuel consumption q_h and q_r for eVTOL can be expressed via engine specific fuel consumption C_e and engine required power P:

(35) $$q_h = C_e P, q_r = \frac{C_e P}{3.6V}$$

Approximate range and endurance calculation for eVTOL with fully electric power plant can be done as following:

(36) $$t = \frac{Q}{P}, L = 3.6Vt$$

Output obtained by formula (36) will be upper estimate as the real battery capacity according to Peukert law is lower than the ideal one due to its dependence of dump current intensity and of the power plant required power respectively.

Obtained functional relationship of the eVTOL power plant required power, range, endurance, as well as eVTOL trimmed value of the resultant thrust vector related to flight velocity are shown on Fig. 12-21. Within the speed envelope up to 220 km/h, among all eVTOL types, a single rotor helicopter with hybrid power plant has the major range and endurance advantage. Quadcopter with open rotors is the obvious top speed performer with 270 km/h. Within the low speed envelope up to 60 km/h, ducted fan quadcopter with both hybrid and fully electric power plant has the maximum vertical speed. Ducted fan high efficiency factor at hover and low speed mode explains this feature.

Amongst vehicles with fully electric power plant, quadcopter with open rotors possesses the major range and endurance advantage at speed of 120 km/h. It occurs due to the high relative capacity of its batteries (38,4 % of vehicle mass against 28,5 % of single rotor helicopter).

Also, it should be noted that quadcopters would have approximately by 50 % higher speed compared with single rotor helicopter.

As far as the highest possible performance with the existing electric motors and batteries specific parameters concerns, eVTOL with hybrid power plant will have the best benefit nowadays. Such eVTOLs would have 2 – 2,5 times more range and endurance values as compare as fully electric vehicles.

4. CONCLUSION

Based on eVTOL aerodynamic prediction results we may conclude that competitive flight vehicle accommodating up to 4 passengers can be designed as an urban airtaxi. It would be possible upon existing today and being emerged in the nearest future technology level.

Fully electrical power plant with batteries as the only power source could be used for the development of eVTOL with cruise flight endurance at about 30 – 40 min and range of 100 – 130 km. Such performance is quite acceptable for using vehicle as an urban airtaxi.

Vehicles with hybrid power plant and 170 – 330 km range would be better employed as intercity transport. For skyscraper downtown intracity flights, ducted fan quadcopter eVTOLs will have undoubted advantage due to its high rate of climb.

5. SYMBOLS AND ABBREVIATIONS

C_T – rotor thrust coefficient
D_{MR} – main rotor diameter
D – VTOL drag
G – VTOL take-off weight
R – rotor radius
L – flight range
t – flight endurance
m_0 – VTOL take-off mass
m_f – ICE fuel weight (in case of hybrid power plant)
m_{trans} – mechanical transmission mass
$\overline{m}_{FC}$ – flight control system mass fraction
$\overline{m}_{Ch}$ – chassis mass fraction
$\overline{m}_{HE}$ – heat engine mass fraction
$\overline{m}_a$ – airframe mass fraction,
$\overline{m}_{FS}$ – fuel system mass fraction
$\overline{m}_{OS}$ – oiling system mass fraction
$\overline{m}_{EM}$ – electric motors mass fraction
$\overline{m}_{GEN}$ – generators mass fraction
$\overline{m}_{rs}$ – rotor system mass fraction
$\overline{m}_{ae}$ – conventional airborne equipment mass fraction

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$\overline{m}_{ue}$ – utility airborne equipment mass fraction
$\overline{m}_{ew}$ – electrical wiring mass fraction
M_0 – rotor tip Mach number in hover mode
$\overline{H}_D$ – relative diffuser length (divided by fan radius)
$\overline{N}_{\mathrm{EM}}$ – thrust electric motor specific power (main gearbox assembly)
$\overline{N}_{gen}$ – generator specific power
$\overline{m}_{bat}$ – battery specific mass
$\overline{m}_{inv}$ – invertor specific mass
n_{MR} – main rotor number
v – induced velocity
$\overline{N}_{\mathrm{HE}}$ – heat engine specific power
C_e – specific fuel consumption
N – thrust engine power
P_i – induced power
P_0 – profile losses power
P_w – shock wave drag power
P_p – parasite drag power
Q – battery capacity, kW/h
T – main rotor thrust
V – eVTOL speed
α – rotor angle of attack
α_D – diffuser angle
μ – rotor performance coefficient
λ – inflow ratio
η – main rotors efficiency factor
χ – rotor disk area usability factor
ξ – transmission efficiency factor
ρ – air density
Ω – main rotor NR.

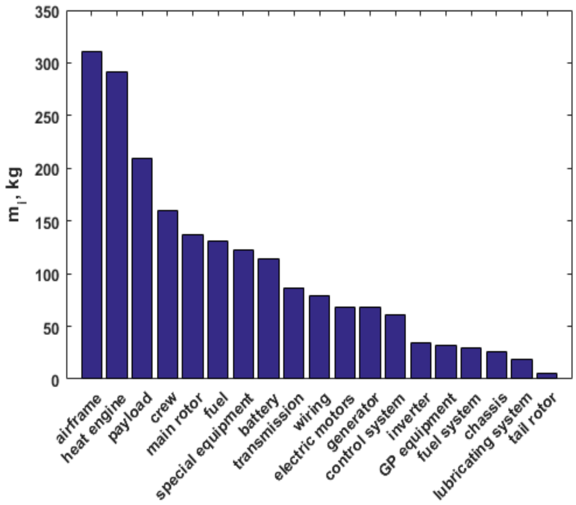

Figure 6. Single rotor helicopter structure elements mass distribution. Hybrid power plant

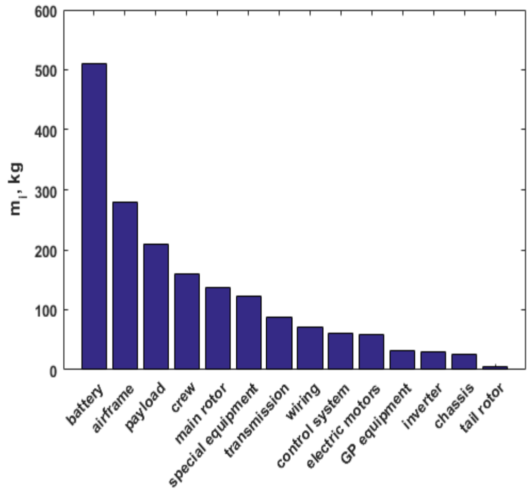

Figure 7. Single rotor helicopter structure elements mass distribution. Fully electric power plant

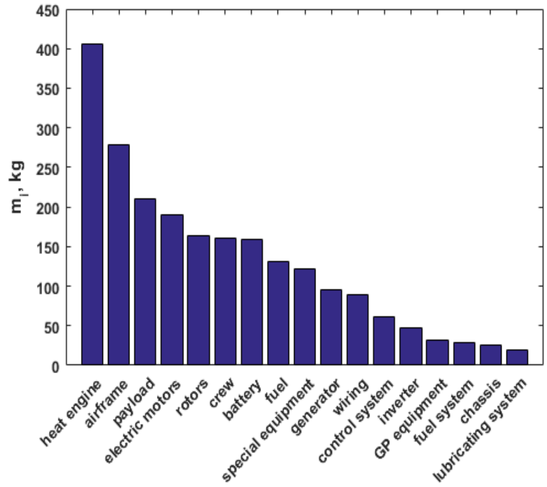

Figure 8. Open rotors quadcopter structure elements mass distribution. Hybrid power plant

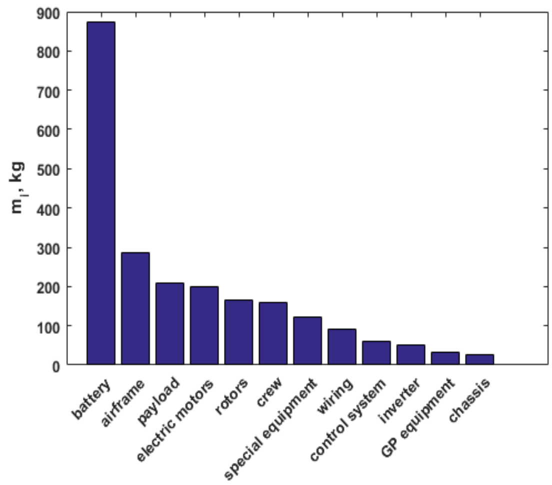

Figure 9. Open rotors quadcopter structure elements mass distribution. Fully electric power plant

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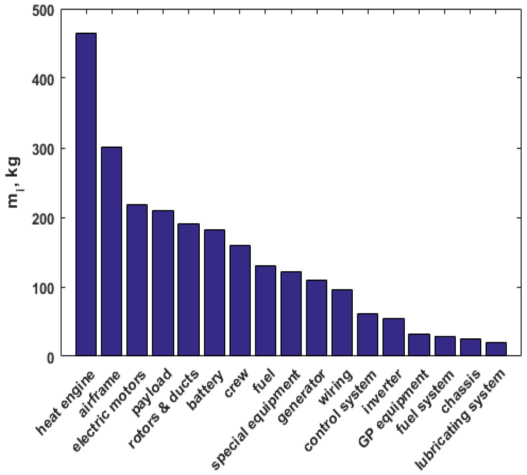

Figure 10. Ducted fans quadcopter structure elements mass distribution. Hybrid power plant

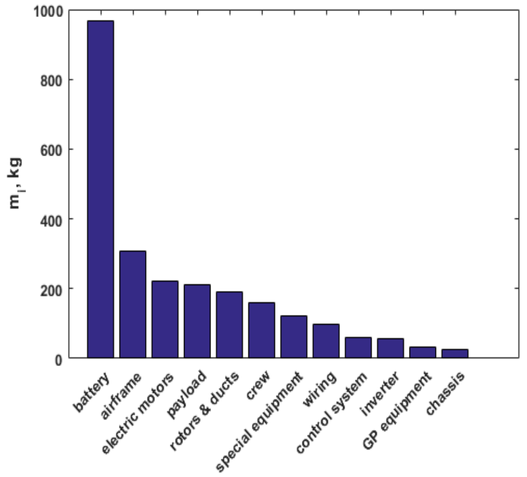

Figure 11. Ducted fans quadcopter structure elements mass distribution. Fully electric power plant

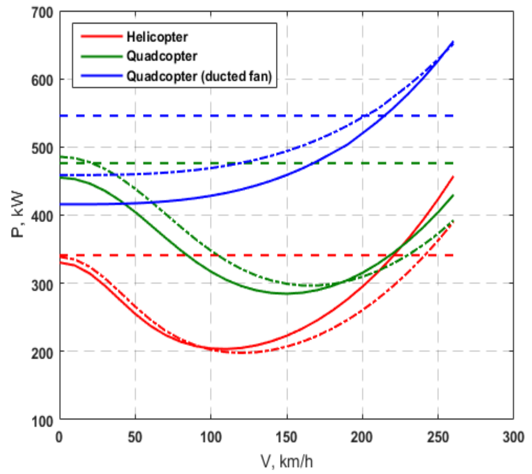

Figure 12. Required power functional connections depending on flight speed. Solid graphs – H = 0 m, dash-dot lines – H = 2000 m, dashed line – power available. Hybrid power plant

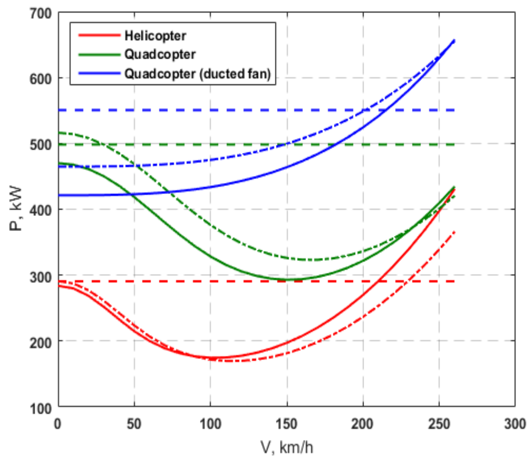

Figure 13. Required power functional connections depending on flight speed. Solid graphs – H = 0 m, dash-dot line – H = 2000 m, dashed line – power available. Fully electric power plant

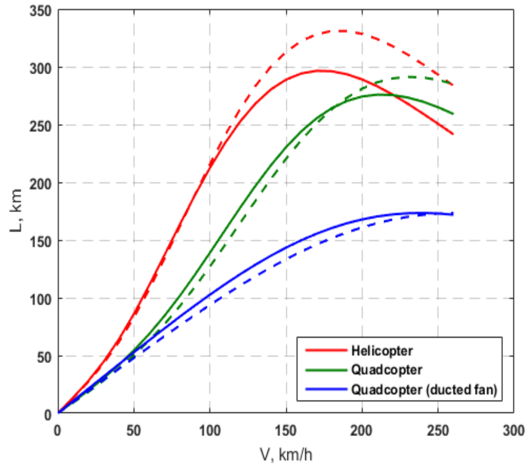

Figure 14. Range functional connection depending on speed. Solid graphs – H = 0 m, dashed lines – H = 2000 m. Hybrid power plant

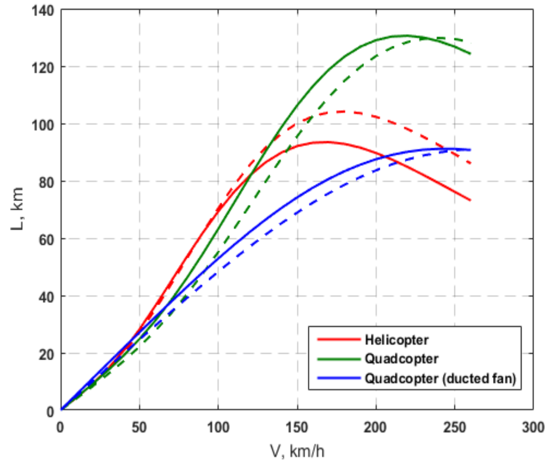

Figure 15. Range functional connection depending on speed. Solid graphs – H = 0 m, dashed lines – H = 2000 m. Fully electric power plant

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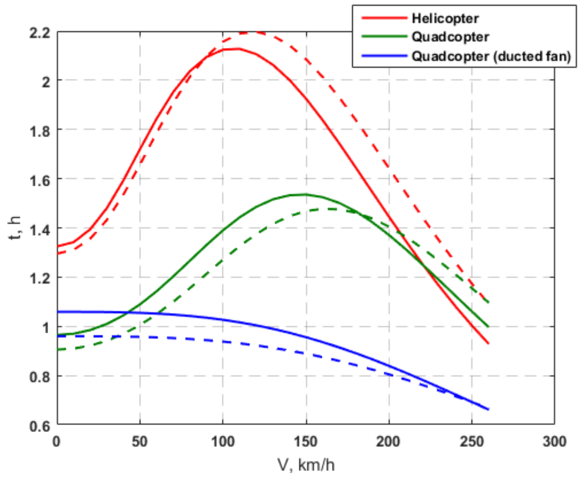

Figure 16. Endurance functional connection depending on speed. Solid graphs – H = 0 m, dashed lines – H = 2000 m. Hybrid power plant

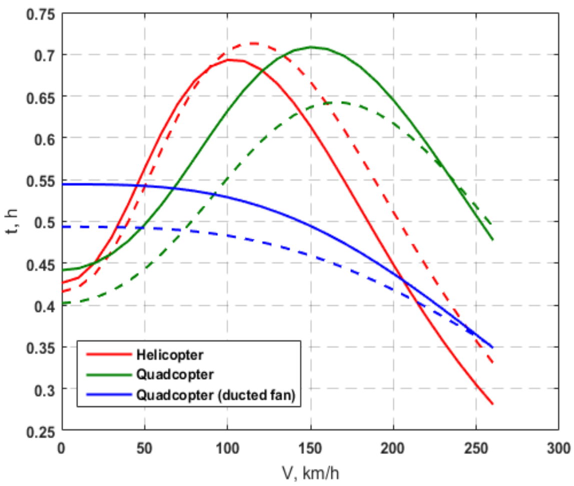

Figure 17. Endurance functional connection depending on speed. Solid graphs – H = 0 m, dashed lines – H = 2000 m. Fully electric power plant

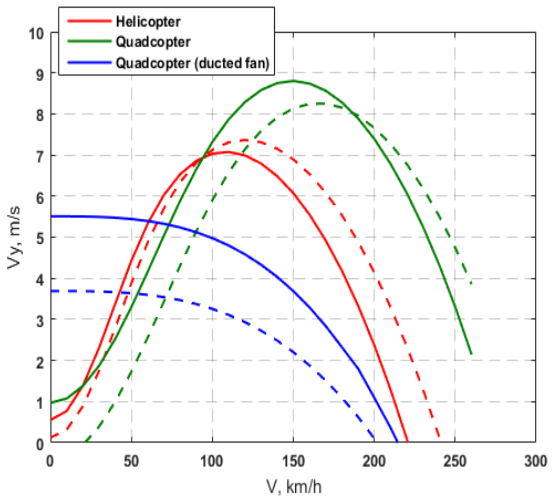

Figure 18. Vertical speed functional connection depending on speed. Solid graphs – H = 0 m, dashed lines – H = 2000 m. Hybrid power plant

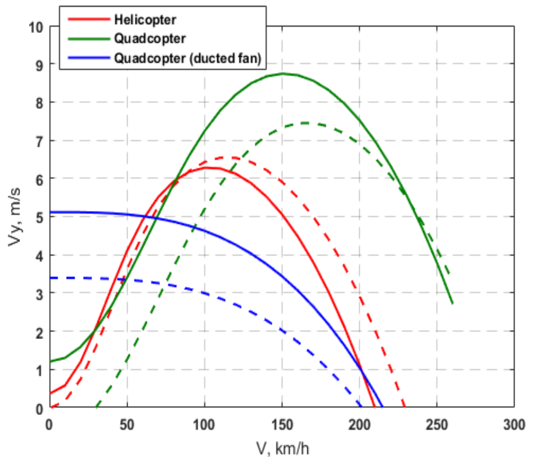

Figure 19. Vertical speed functional connection depending on speed. Solid graphs – H = 0 m, dashed lines – H = 2000 m. Fully electric power plant

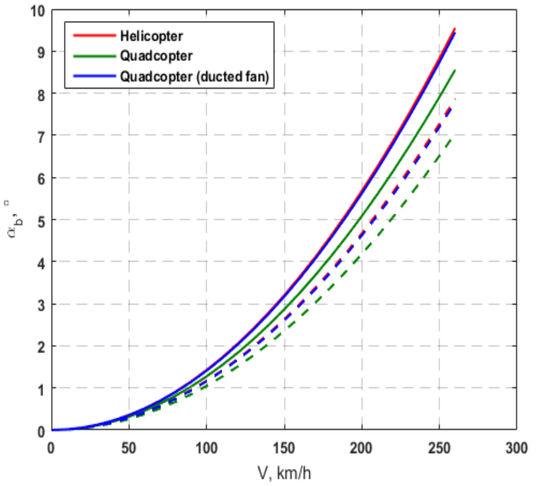

Figure 20. eVTOL resultant thrust vector mistrim depending on flight speed. Solid graphs – H = 0 m, dashed lines – H = 2000 m. Hybrid power plant

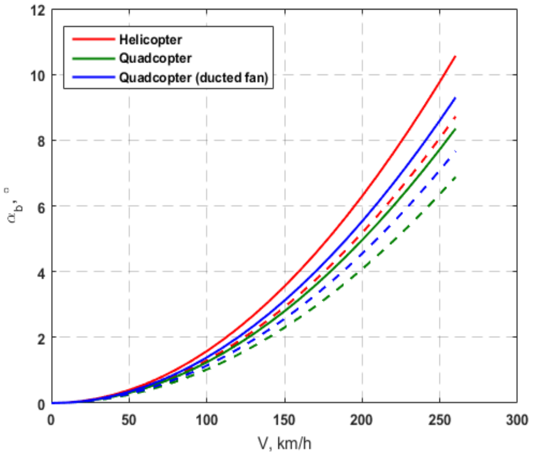

Figure 21. eVTOL resultant thrust vector mistrim depending on flight speed. Solid graphs – H = 0 m, dashed lines – H = 2000 m. Fully electric power plant

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