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OPTIMIZATION OF ENERGY CONSUMPTION IN THE TRANSITION STATE OF A QUAD-PLANE

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Abstract

The paper presents the problem of minimizing energy consumption by a UAV designed in the quad-plane configuration. The phase which consumes a big amount of electric energy is the transition from the vertical to the horizontal flight. Therefore, the optimization of the profile of this phase is crucial to improving the performance characteristics.

Keywords: UAV, VTOL, quad-plane, optimization

1. Introduction

The problem of minimizing energy consumption by an unmanned aerial vehicle that has VTOL (Vertical Take-Off and Landing) capabilities is crucial from the general performance point of view. The presented UAV is designed in the quad-plane configuration that combines VTOL characteristics with fast forward flight capability. This is a so-called hybrid UAV (VTOL + Fixed Wing) that is often designed and built in the last years [1]. All power units for the VTOL capability are electric and it has to give thrust greater than the take-off weight. In the presented UAV motors are doubled for redundancy purposes, while the maximum T/W (thrust-to-weight ratio) is about 2.0. Therefore, the VTOL capability causes high energy consumption and due to a relatively low energy density of batteries leads to an increase in their weight, hence limits the payload and range of the aircraft. The phase, which consumes a big amount of electric energy is the transition from the vertical to the horizontal flight. Thus the optimization of the profile of this phase is very significant to improve the performance characteristics, especially range and endurance.

The issue briefly described above was tested during flight tests of PW Chimera – the UAV designed and built at the Warsaw University of Technology [2]. The maiden flight was made in 2021. Already during the design of the aircraft, the problem of the weight of batteries and the entire electric system occurred but was successfully solved [3]. However, during the first flight, the acceleration phase profile as the vehicle transitions from the copter flight to the airplane flight mode was found to be crucial in terms of time, distance and energy consumption.

2. PW Chimera

PW-Chimera is a small (25 kg class) UAV with VTOL capabilities (Figure 1). It was designed as a multipurpose aerial vehicle, mainly to transport of cargo or measuring equipment. The main parameters (geometry, weight, performance) are presented in Table 1.

The primary purpose forced the mission profile. Three basic mission profiles were assumed: cruise(1), loiter-monitoring (2), delivery and return (3). The aircraft was designed with two types of the propulsion system for level flight: an electric motor and a fuel engine (Figure 7). In both configurations, VTOL propulsion was realized with electric motors. Electric motor for a level flight gives reliability, easy maintenance and the aircraft does not need any fossil fuel, which makes it clean and less

Table 1 – Main technical characteristics

Propulsion type	full electric	piston/electric
range (radius)	40 km (20 km)	150 km (75 km)
max. airspeed	80 km/h	140 km/h
operational ceiling	0-150 m AGL	
MTOW	25 kg	
payload	3 kg	
payload dimensions	30x30x50 cm	
wing area	1.2 m^2	
wing span	3.5 m	
mean aerodynamic chord	0.35 m	

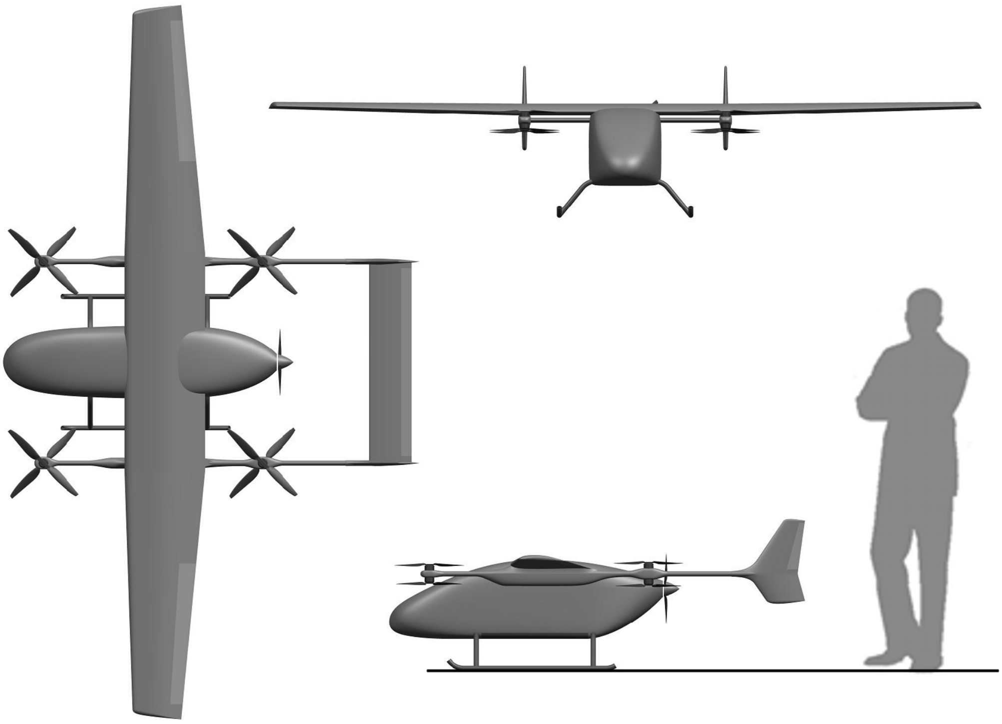

Figure 1 – UAV PW Chimera - 3 projections

complicated. On the other hand, fuel has a much higher energy density, compared to the amount of energy that can be stored in the batteries but does not have the listed advantages of electric propulsion. The VTOL propulsion system should always be electric because of the number of motors required, fast response of control and reliability. The time needed for takeoff or landing in the VTOL configuration was estimated at about 2 min. This relatively short time for vertical maneuvers focused particular attention on all possibilities of reducing electricity consumption by VTOL drives. Since vertical take-off takes about 20 seconds and landing 10-15 seconds, it is clear that optimizing the transition phase can offer the opportunity to save energy for vertical maneuvers and thus increase overall flight safety.

3. Physical and mathematical model

In order to optimize the transition phase of flight, an appropriate physical and mathematical model has to be applied. In this phase, the aerodynamic characteristics vary with significant speed changes and they are a sort of mixture of the forward flight and hover characteristics. The general case of the forces acting on the UAV is presented in Figure 2. Eight propellers (copter flight) support the lift force created on the wing. Due to the negative pitch angle, the horizontal component of hoovering propellers thrust gives a significant increase in total forward thrust supporting the thrust from the forward flight motor unit. On the other hand, the wing has a decreased lift coefficient and may produce additional drag. The key is to find an optimum change in time of the angle of attack during the transition flight. To derive the mathematical model the following assumptions were given:

- the vertical component of the VTOL motor thrust (T_V) and the lift force (L) balance the weight (Q) and the forward flight unit vertical component of the thrust T_M,
- the total horizontal thrust (horizontal components of T_V and T_M) is reduced by the aerodynamic drag (D),
- power unit for the forward flight works to give maximum thrust and depends on the airspeed only,
- VTOL motors are stopped when L>=Q or V>=1.1 V_{min}.

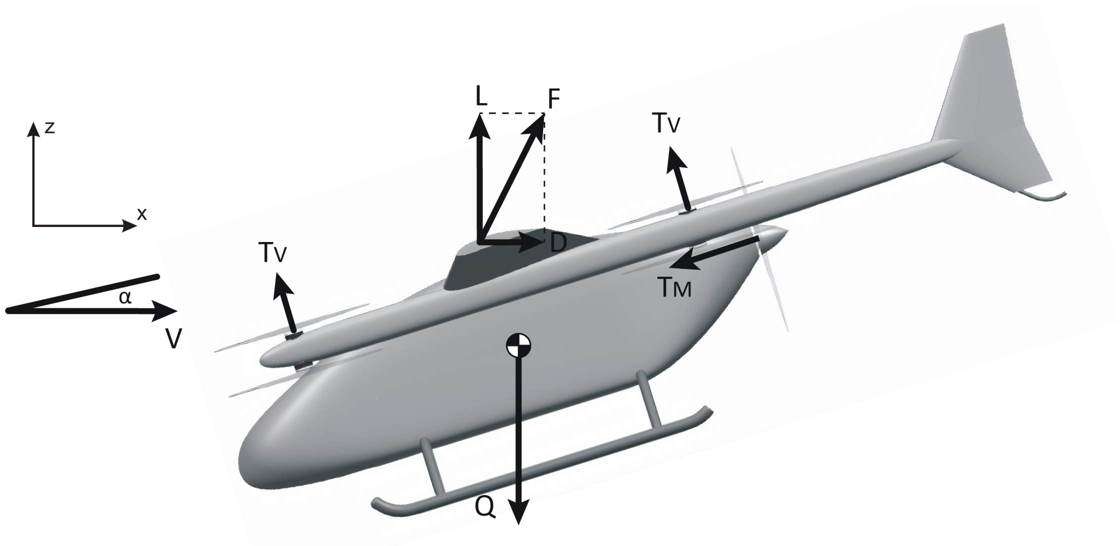

Figure 2 – UAV PW Chimera during the transition phase

The equation of motion (3 DoF model), taking into account above assumptions and using notation presented in Fig. 2, can be written as follows:

$$\begin{aligned} m\ddot{z} &= \sum F_z = L(\alpha,V) + 4\ T_V(V)cos\alpha + T_M(V)sin\alpha - Q \\ m\ddot{x} &= \sum F_x = -D(\alpha,V) - 4\ T_V(V)sin\alpha + T_M(V)cos\alpha \\ I\dot{q} &= \sum M_y \end{aligned} \tag{1}$$

Taking into account the condition of level flight ($\sum F_z = 0$) and assuming that sum of pitching moment is balanced, average thrust of VTOL units should be equal to:

$$T_v(V) = \frac{Q - L(\alpha,V) - T_M(V)sin\alpha}{4\ cos\alpha} \tag{2}$$

and resultant equation of horizontal acceleration:

$$m\ddot{x} = \frac{(L(\alpha,V) - Q)sin\alpha + T_M(V)}{cos\alpha} - D(\alpha,V) \tag{3}$$

The relation between power and thrust of VTOL units can be written as follows [4]:

$$P = \frac{T_V(V)^{3/2}}{\sqrt{2\rho A}} \tag{4}$$

where: ρ - air density, A - reference area (propeller disc area).
Thus the total energy consuming can be computed using the integral:

$$E = 4\int_0^t Pdt \tag{5}$$

4. Computation & results

The above presented mathematical model allows to formulate the ODE (Ordinary Differential Equation) problem to compute the necessary energy for the transition phase (Eq. 5) and distance covered during acceleration (Eq. 3). The balance of the lift component and the weight of the airplane is the stop condition, which is supplemented by the limit value of the airspeed of 25 m/s.
First the energy consumption was computed for the constant values of the AoA that and for the AoA being a function of speed defined by a third-order polynomial, starting with α = -6 degrees (V = 0) and ending with α = 0 degrees for V = 25 m/s. The results are presented in Figure 2 and Table 2.

Table 2 – Comparison of the results for the constant AoA and using the 3rd order polynomial

alpha [deg]	W [J]	V [m/s]	x [m]	t [s]
0	37007.2	24.04	497.8	31.7
-2	40216.9	25	380.1	24.1
-4	40282.7	25	242.8	16.6
-6	38667.6	25	168.1	12.3
α **(V)**	29985.4	22.56	312.4	20.3

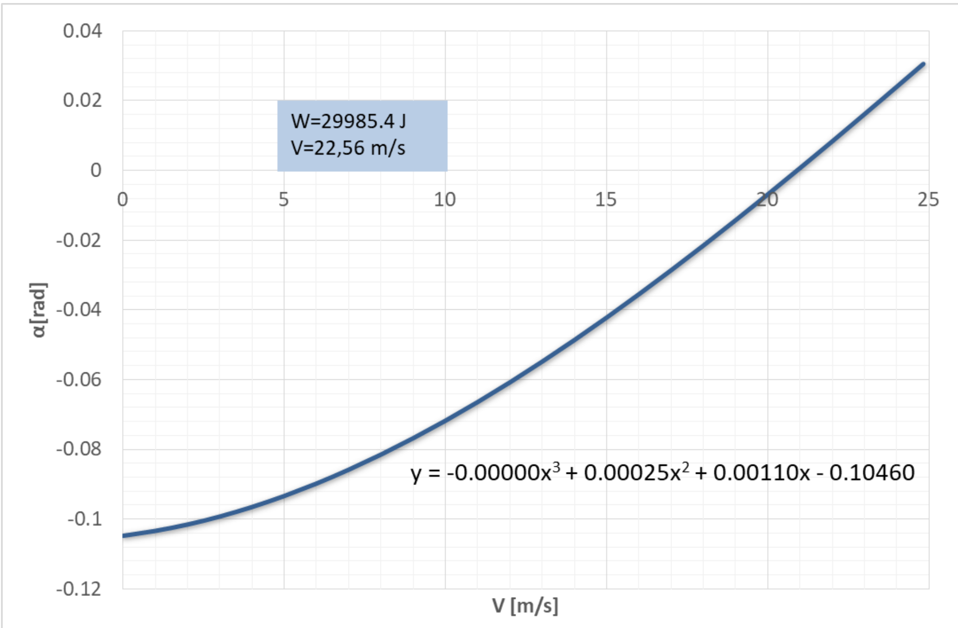

Figure 3 – The polynomial function describing the semi-optimal relationship between the AOA and the airspeed

The assumptions presented above allowed determining the optimized trajectory [5] and the optimal pitch angle change in time (equal to the angle of attack as the path angle is equal to zero) versus the gained airspeed. The next step was the numerical optimization of the transition phase by minimization of the energy consumption. The coefficients of the polynomial were the optimization variables and the final results were obtained by using the OptiM package [6] with different methods as presented in Figure 4 and Table 3.
Defined above ODE problem (Eq.3-5) forms the kernel of the objective function of the optimization problem, that can be formulated as follows:
Minimize: energy consumption (Eq.5)
with respect to:
$X = \{AA, BB, CC, DD\}$,where:

$$\alpha(V) = AA\,V^3 + BB\,V^2 + CC\,V + DD \tag{6}$$

subject to:

$-8.5 < \alpha < 8.5$ [deg] - subcritical range of AoA
$T_V < 1.7\ Q/4$ - max. thrust of VTOL units, assuming 70% thrust exceed vs. MTOW.

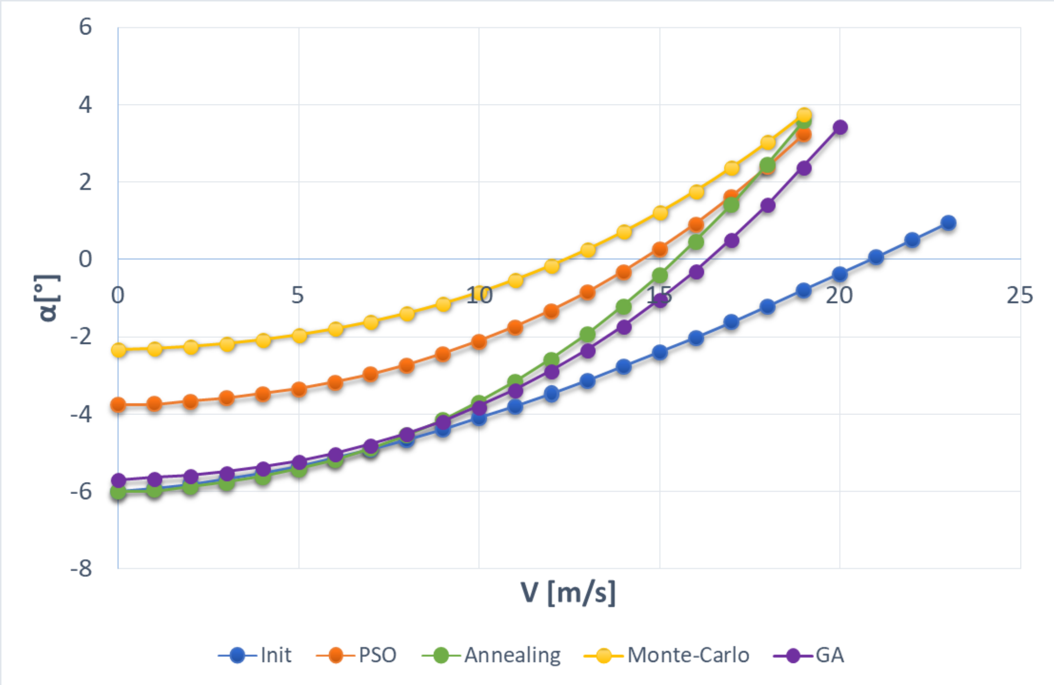

Figure 4 – Comparison of the α (V) functions derived using different optimization methods

Table 3 – Comparison of the results obtained with different optimization methods

Case	Final velocity [m/s]	Final AoA [deg]	Consumed energy [J]	Time [s]	Distance [m]
Initial case	22.56	0.74	29 985	20.25	312.4
PSO	19.02	3.25	27 114	17.15	213.3
Annealing	18.84	3.40	25 066	15.05	189.5
Monte-Carlo	18.72	3.54	28 347	18.55	223.4
Genetic Algorithm	19.45	2.85	26 008	15.70	203.0

5. Mathematical model vs. Wind tunnel tests

The results presented above were obtained assuming a simplified mathematical model defined by Eq.2, where the influence of VTOL units is modeled by the appropriate component of thrust created by these units. The impact of VTOL propellers drag, however, can be significant [7]. The experimental tests in the wind tunnel [8] allowed obtaining reliable data on VTOL propeller thrust and drag in airflow, which was taken to correct the influence of VTOL propellers on the UAV during the transition phase and to improve results from the first optimization stage. The difference of X component of force acting on the UAV (right-hand side of Eq.2) versus AoA presents graph in Fig.5. The figure presents the results of the wind tunnel tests for air flow velocities up to 20 m/s in increments of 5 m/s (marked as WT), as well as from the simple model presented in the previous section (marked SIMPLY on the graph). The comparison of the two models shows that the increment of forward thrust due to the negative pitch angle (AoA) is lesser than this resulting of VTOL units thrust only, especially in the case of higher airspeed. Moreover, the propellers effect significantly reduces the resultant X force (Eq. 2), causing a reduction in acceleration.
These results made it necessary to repeat the optimization procedure with a modified mathematical model. The x component of the aerodynamic forces was derived as a function of airspeed and angle of attack using a complex approximation of the experimental results.

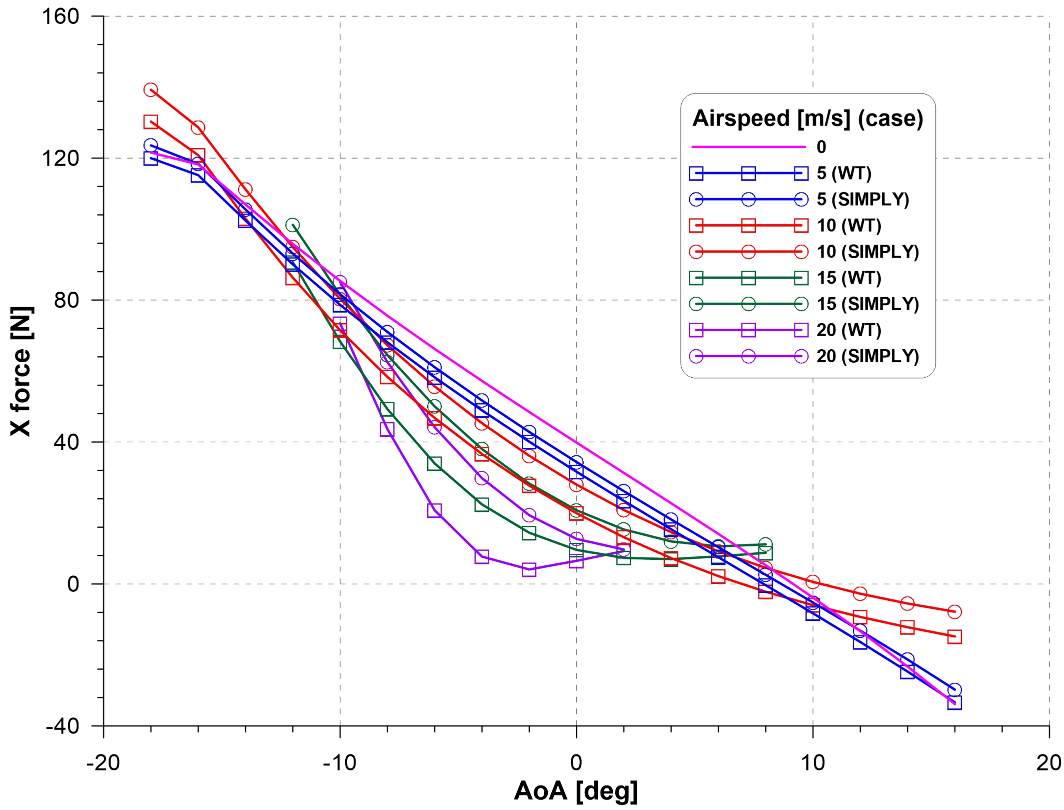

Figure 5 – X force component

The optimization problem itself has been defined similarly to the previous one. The calculations were also repeated for the constant values of the angle of attack. The results obtained for AoA equal to zero using a model derived from wind tunnel tests gave almost 56kJ, while in the case of the simplified model only 37kJ. Therefore quite big differences were expected.

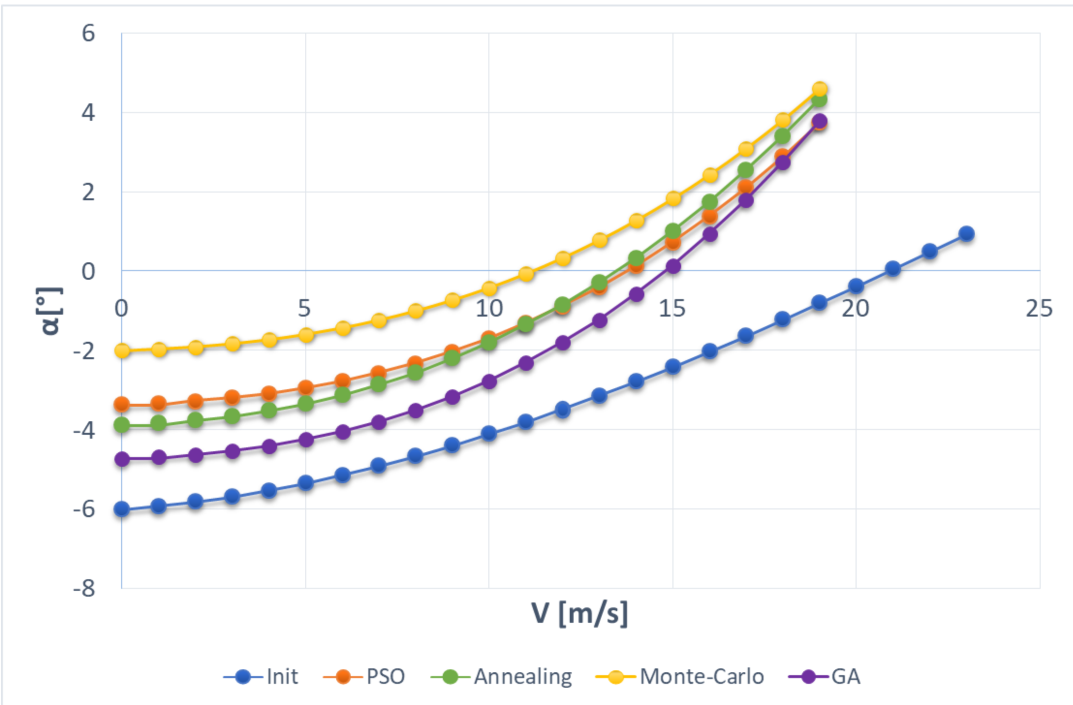

Figure 6 – Comparison of the α (V) functions derived using different optimization methods - modified model

Table 4 – Comparison of the results obtained with different optimization methods - modified model

Case	Final velocity [m/s]	Final AoA [deg]	Consumed energy [J]	Time [s]	Distance [m]
Initial case	22.55	0.74	47 882	34.85	571.0
PSO	18.73	3.51	37 815	25.75	333.1
Annealing	18.44	3.82	36 568	24.90	319.0
Monte-Carlo	18.25	4.01	39 181	27.40	339.2
Genetic Algorithm	18.74	3.50	36 058	23.80	313.2

The results presented in Fig.6 and in the Table.4 show that the effect of flight trajectory optimization in the case of more realistic data is even more significant and amounts to approx. 20 kJ compared to the case of a constant angle attack equal to zero degrees.

6. Concluding remarks

The presented analysis gave interesting results and showed that simplified models, very convenient in flight mechanics problems, can be insufficient and can give severely distorted results. However, the results allow to formulate the following concluding remarks:

- the change of pitch angle versus airspeed is very reasonable and can save about 15-20 kJ of energy, which is about 30% of that needed in the transition phase, in case of constant pitch angle,
- optimization procedure can determine the flight path that allows a smooth ending of the transition phase,
- model should be complemented with the translation of the mechanical energy to electric energy (motor characteristics), to obtain more realistic results,
- the obtained flight path is a good starting point to design the optimal control of UAV in the transition phase.

Two versions of the vehicle are designed: fully electric (propulsion systems for the forward flight and VTOL are electric) and mixed where the forward flight unit is a piston engine (Figure 7). Parallelly executed flight tests of the two built prototypes provided additional information. The optimal trajectory (pitch angle versus airspeed) depends strongly on the pusher unit characteristics. In the case of the fully electric version, the profile of the transition phase plays a much more important role in the reduction of the energy consumption while in the case of the piston engine the acceleration is much higher. Due to the thrust excess, the electric energy consumption is much lower and the profile is not so crucial.

Figure 7 – Two PW Chimera: full electric (left), mixed propulsion (right)

Although the PW Chimera version with the mixed propulsion system is not as sensitive to the transition phase profile, the fully electric version is the target version due to the environmental advantages, both in emission and noise. Therefore, the optimization of the trajectory is an important issue just as the typical design optimization problems are [9]. The design of the optimal control is the next step for future work.

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8. Copyright Statement

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