DEVELOPING THE UNMANNED UNCONVENTIONAL CARGO AIRPLANES WITH HYBRID PROPULSION SYSTEM

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Keywords: *hybrid propulsion, cargo UAV, unconventional form*

Abstract

The lecture deals with developing a family of unmanned hybrid cargo aircraft that may transport the goods for 100 – 300 km distances in small cargo containers of 50 - 1000 kg. The lecture analyses the conceptual design of aircraft, problems and barriers of developing the full electric and hybrid aircraft and introduces a new conceptual design method by defining extra constraints for mass and energy balances (sum of component fractions). The new concept is tested and applied to developing the special cargo UAV series. After definition the operational concept, a family of unconventional form hybrid aircraft are developed and their characteristics, mass and energy balances are discussed. The airplanes are optimized for life cycle.

1 Introduction

The leaders and policy makers of aviation have defined very ambitious goals as developing the sustainable air transport including reduction in CO_2 emission for 75 % and NO_x for 90 % until 2050 or reducing the accidents rate for 80 % [1]. One of the possible solution promises reaching these goals is developing new unmanned full electric / hybrid cargo aircraft.

The unmanned aircraft, unmanned air systems are developing very rapidly. It seems the military applications push on technology development, while the market needs pull the wider civilian deployment.

The technology is ready to develop the cost effective unmanned cargo aircraft. There are two group of such aircraft are under development. On one hand, the relatively large airplanes are planned for transport loads 1 – 10 t with range from 400 up to 4000 nm and speeds of 150 or 300 knots. Such planes (Fig. 1.) are called as unmanned cargo aircraft (UCA) or Platform for unmanned cargo aircraft (PUCA) [2]. On the other hand, the small unmanned aircraft as drones support delivery of goods for relatively short distances.

Fig. 1. An idea: platform for unmanned cargo aircraft [2]

This lecture deals with unmanned cargo aircraft that may transport the goods for 100 – 400 km distances, in small cargo containers from 50 kg up to 10 hundred kg. These aircraft may deliver goods from warehouses to local distribution centres, transferring the cargo, daily delivery cargo between the central or regional airports and small airports, airfields or delivery the 3D printed elements to the users between the innovation parks and small producers.

The lecture has two major parts. First investigates the problems, barriers interfering the electric / hybrid aircraft developments, and introduces new conceptual design methodology based on definition extra constraints on the energy and mass balances.

The second part describes the developed new conceptual design methodology, its testing and applying to developing the special family of cargo UAVs with hybrid propulsion system and unconventional forms. The paper discusses the applicable unconventional forms, characteristics, mass and energy balances of the developing UAVs. The airplanes are optimized for life cycle.

2 Problems and barriers of electric aircraft

All the problems, constrains and barriers balking the quicker deployment of the electric and hybrid propulsion systems are initiated by the relatively low technological level of the available accumulator technologies, available batteries [3].

Fig. 2. shows the characteristics of the electric batteries comparing to the gasoline (jet fuel) [4 – 6].

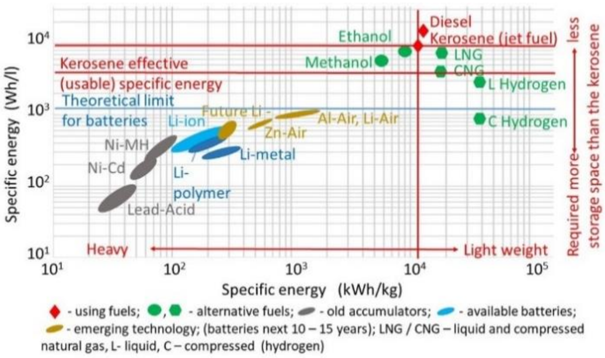

Fig. 2. Energetic comparison of the applicable fuels

Several problems can be explained by this Figure. At first, the specific energy of kerosene about 30 – 40 times greater than the specific energy of the available batteries. By taking into account the total efficiency of the propulsion systems (equal to about 24 – 28 % in case of conventional and around 76 – 82 % in case of full electric systems including the propellers' efficiency, too), a kg of kerosene contains usable (useful) energy that might be stored by 12 – 13 kg batteries [3]. That means 1 litre kerosene supports the aircraft by useful energy, storage of which in electric form required 9 – 10 kg batteries.

Already this fact may explain why the technology has not allowed yet to develop a full electric aircraft with performance similar to existing conventional ones. Depending on the accepted radical reduction in range, the mass of full electric aircraft increases for 40 - 400 %. For example, Figure 3. demonstrates the changes in relative mass balance of the he possible small size (around 50-seat) regional hybrid aircraft [7] equipped by electric butteries with 500 Wh/kg specific energy (that unit is about 60 – 70 % greater than specific energy of the today available batteries). In case, when electrification (ratio of electric energy and total energy using during the absolving the full flight mission) reaches 75 %, than the relative mass of commercial load reducing for 48 %, from value 25,8 % to 13,1 %. At the same time, the take-off gross mass increases for 96 % the required wing area for 134 %. So, such large electrification today is not realizable.

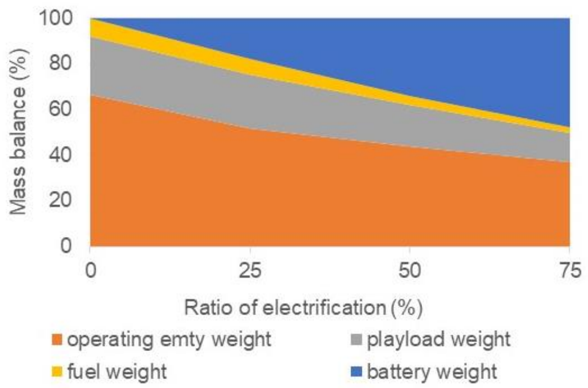

Fig. 3. Mass balance (fractions) of the middle size regional hybrid aircraft depending on electrification (drawn by use of results published by Antcliff et al. [7])

It seems, this technological barrier (low energy density) is not hard, because the sciences and technologies are developing very actively in accelerated form and the diffusion time of new product into the market considerable and continuously reduces. At first, as it can be seen in Figure 2. the specific energies of the available lithium-ion, lithium-polymer are close to their technical limits. The future, emerging technologies allow to develop aluminium-air, lithium-air accumulators, which may have already the acceptable specific energy density. At second, the accumulator technology developments are not follow the Moore's law [8], according to which the transistors on a chip doubles every year while the costs are halved. So, the availability of the required emerging accumulator technologies at 2030 – 2035 might be too optimistic expectation.

Plus to it, the emerging accumulator technology may reach the theoretical limits of the known battery technologies. For success absolutely new energy storage technology should be developed.

The media, green organisations, foundations and generally the societies cause another interesting problem by accepting diffusing and propagandizing a "governing" principle; the electric aircraft are absolutely green vehicles with zero emission. They are forgetting about the emissions of electric energy generation, production the accumulators, aircraft, building the required infrastructure, etc. The taking into account all these effects and determining the total environmental impacts, the picture is not so nice [9].

Figure 4. demonstrates how the small aircraft emissions depend on the types of propulsion systems. Here conventional aircraft is a theoretical conventional 4 - seaters aircraft (analogical to Cessna 172). The electric 200, 400 and 600 mean full electric aircraft equipped by batteries of 200, 400 and 600 kWh. While the hybrid 15 and 45 depict the hybrid aircraft may fly in full electric modes 15 or 45 minutes.

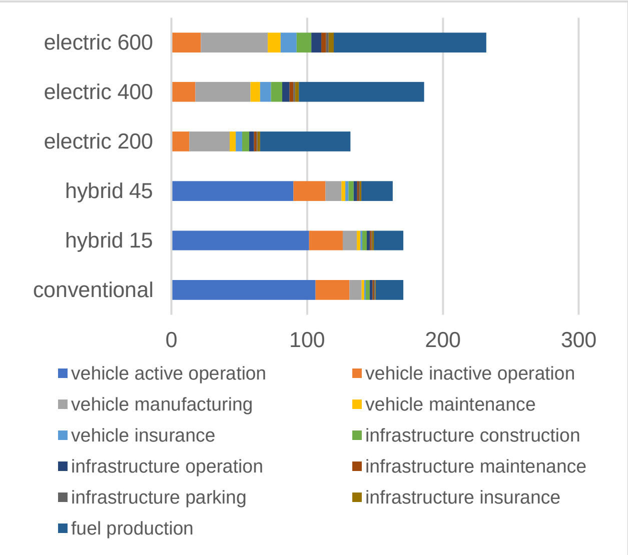

Fig. 4. The total life cycle CO_{2e} emission of the investigated aircraft (electric aircraft with buttery banks 600, 400, 200 KWh, hybrid aircraft applying only electric power for 45 or 15 minutes during its flight) (g/pkm)

This Figure calls the attention: the available batteries technologies (even the emerging) cannot allow to develop the full electric aircraft with the performance analogical to current conventional aircraft (even according to their ecologic greening). The hybrid aircraft with light hybridization factor (equals to 10 – 25 %) may reduced the environmental impact in airport regions and generally the total emission for 4 – 7 %

3 A new approach to aircraft conceptual design

The aircraft design process is a multidisciplinary nonlinear optimization process with large series of (legal, economic, technological, mechanical, aerodynamic, flight performance, flight mission, flight dynamics, stability, control, etc.) constraints [3]. For example, the legal constraints are defined by the airworthiness requirements as mechanical (stress, weight) constraints or as flight performance, stability and control criteria. For instant, the very light airplanes (with take-off mass less than 750 kg and stalling speed less than 83 km/h) should have take-off distance (horizontal part of flight path from start up to reaching the 11 m above the take-off surface) less than 500 m [10]. According to the Certification Specification, CS 23 [11], the normal, utility and aerobatic category reciprocating engine-powered aeroplane of 2 722 kg or less maximum weight must have a steady gradient of climb at sea level of at least 8.3% for landplanes and 6.7% for seaplanes and amphibians with retracted landing gears and flaps in take-off position. The analogical aeroplanes with gas turbines and extended landing gear should have 4 % steady gradient of climb after take-off. In any case, the regulations as usually follow only the technological changes.

The well-known and applied methods of the aircraft conventional conceptual design [12 – 14] were adapted to electric and hybrid aircraft design by several institutions, universities [7, 15-19]. The applied methodologies include three groups of improvements: (i) reformulation of the operation concept and mission, (ii) correcting the weight/mass formulas and (iii) improving the aircraft performance (range) determining methods.

Figure 5. shows the improved conceptual design methodology. The operational concept derived from market needs allowed by available and emerging technologies and qualified by the airworthiness requirements. All these provide inputs for the conceptual design.

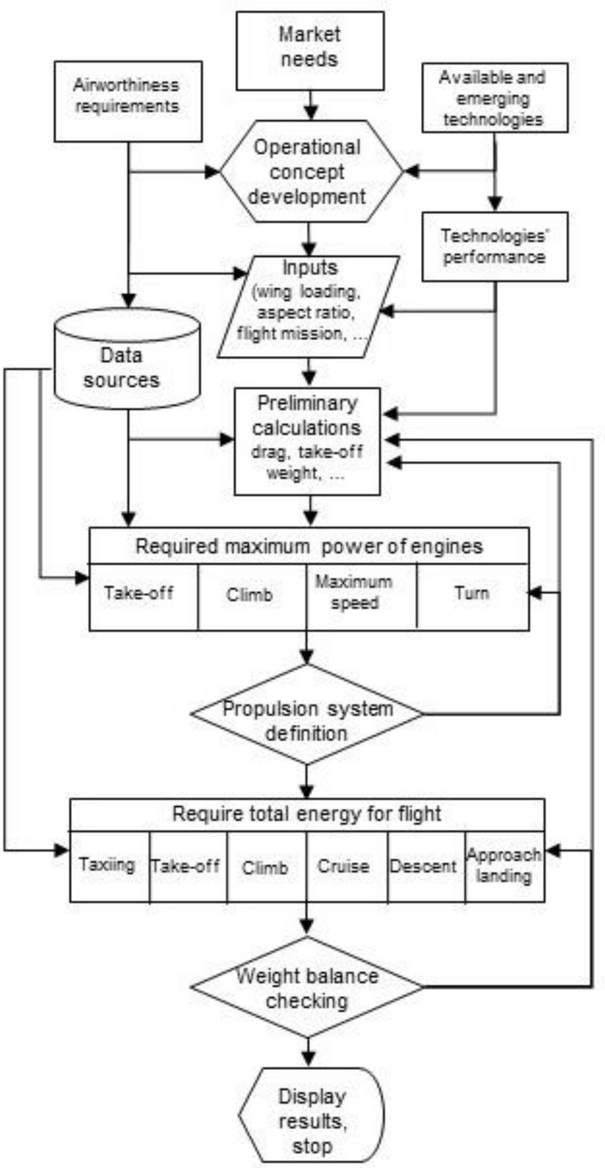

Fig. 5. The conventional conceptual design methodology adapted to developing the electric and hybrid aircraft

The preliminary calculation uses the available data on the existing solutions, constructions, aerodynamic, etc. characteristics of analogical aircraft and theoretical and semi practical methods and provides the aerodynamics coefficient, preliminary defined mass balance as set of harmonised mass fractions of mass components and relative masses (weights), etc. supporting the future studies.

There are two major cycles embedded. First deals with calculation of the required power. The second determines the total required energy for supporting the full flight mission. The objectives of these actions are the synthesis the full aircraft in optimal form depending on the constraints.

The conceptual design might be stop, if the weight balance checking demonstrates the acceptable and realizable results. Of course the aerodynamics, flight performance, stability and control, etc. requirements should be complied, too.

This conventional conceptual design methodology has applied for developing five types of 4-seat small aircraft with different propulsion systems [3, 20]. The aircraft performance were compared with a hypothetical conventional aircraft analogical to Cessna 172N with range 1300 km and cruise speed 226 km/h. The batteries of developing aircraft ries may storage the 200, 400 and 600 KWh.

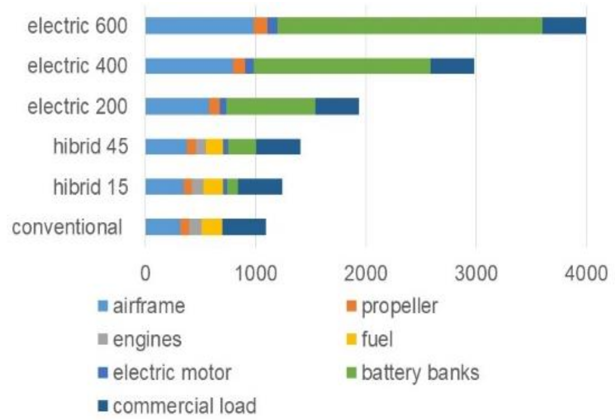

Fig. 6. The mass breakdown (kg) of the analysed aircraft

Figure 6. shows the mass breakdown of the conceptually designed and evaluated aircraft. It demonstrates the full electric aircraft take-off mass (total mass in the figure) increasing exponentially. At the same time, the aircraft electric 200, 400 and 600 have range, only, 28, 40 and 49 % of the conventional aircraft range.

Figure 6. confirms the full electric aircraft cannot be realized by use of the available battery technologies and conventional conceptual design methodology. Therefore a new approach to conceptual design had been developed. This methodology includes further constraints on relative masses, required energies of the different flight mission elements and reduction in performance (like accepted reduction of range).

The developers might define these new constraints partly subjectively.

Figure 7. proves an examples of mass balance of such electric aircraft that developed by using the predefined additional constraints (as

limitation on the relative mass of airframe) comparing with conventional and electric 600 aircraft. As it can be seen, the electric predefined aircraft has relative mass of power storage system (batteries) considerable smaller than the electric aircraft 600 (designed by using the conventional conceptual methodology) but – of course – much more greater than the mass of fuel used by conventional aircraft.

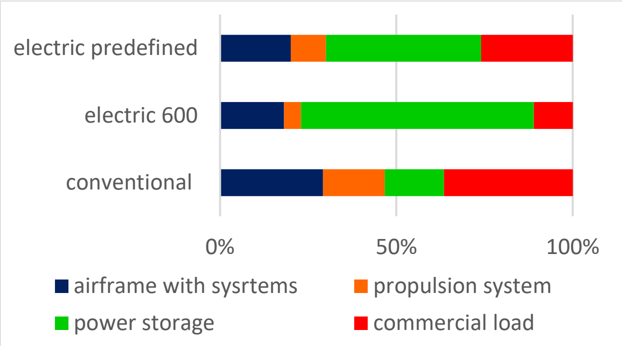

Fig. 7. Limitation on the mass balance (conventional, electric 600 and future electric aircraft

Using extra constraints on mass and energy balance requires developing very special aircraft, operating by applying radically new solutions. For example, the mass of airframe can be reduced by deployment of the new materials, lightweight flexible airframe, like wing (of course with gust effect elimination and life management), structural solutions based on biological analogies (biomimicry), etc.

The accepting reduction in flight performance, less cruise speed, longer take-off distance, etc. may lessening the mass of required batteries.

The radically new, original solutions may implement the ideas developing by the use of out of the box thinking [21 – 26], including take-off by ground energy support (Fig.8), aerial refuelling or cruiser – feeder concept.

4 Developing the hybrid cargo UAV

A Hungarian national project [27] supports disruptive technology development. There was defined a professional task, too, to analyse and develop the electric and hybrid aircraft. So, the project team works on conceptual design of a 4-seat small aircraft [20] and cargo UAV. This paper, in following sections, describes and shortly discusses the first results of the conceptual design of family of cargo UAVs with electric / hybrid propulsion systems [28 – 30].

Fig. 8. Take-off and landing assisted by magnetic levitation concept developed by EU supported GABRIEL project [25]

The large cargo UAV developments, as PUKA [2] and small drones' application for goods delivery in cities [3] are well known. However, there are a lack in developing a moderate cargo UAVs. For instant, Boeing develops a special cargo air vehicle as electric vertical take-off and landing (eVTOL) aircraft for transporting goods of weight 339 kg (Fig. 9.).

Fig. 9. The Boeing HorizonX is an unconventional eVTOL cargo air vehicle [32]

It seems there are needs in UAVs may transfer some hundred kg cargo supporting the express delivery carriers, namely - according to the preliminary analysis - 1 – 10 hundred kg commercial load for distance 100 – 300 km. This wide range in required performance calls for developing a series of aircraft. There are three different sizes, but similar aircraft under development. Each aircraft may adopt to transfer 1 – 3 containers. The smallest may hold containers of 50 kg mass, that is to say, the aircraft commercial load might be 50, 100 or 150 kg. It has a range 100 km. The larger airplane may carry containers of 200, 300 or 400 kg mass for distance 200 km.

While the larges can transport goods of 600, 800 or 1000 kg for up to 400 km.

The flight mission is defined very simple: taxiing, take-off, climb, cruise, descent, approach and landing. The cruise modes, (velocity and altitude) are optimized for block time, and actual commercial load. The block time (time from starting the take-off until stopping the aircraft after landing) is defined as 1 hour 30 minutes, 2 hours and 2 hours 30 minutes for the 3 different size of aircraft with full loads. Because the highly adaptive wings the users may operate, the aircraft flying on smaller cruise speed (that increases the block time). The defined take-off distances are 60, 100 and 200 m. Rate of climb might be accepted 4 % for all three modification. This is a little bit more than a minimum prescribed by airworthiness requirements, but because of relatively small climbing speed and possible limited airfield area, the climb rate is defined to reach the 3 m/s.

It seems the largest aircraft carrying 600 – 1000 kg loads is rather similar with small 4 – 6 seats aircraft. On the other hand, developing the smallest version faces critical problems. At least the known smallest aircraft like Cri-Cri (Fig. 10.) or SD-1 have relative empty mass (empty mass per take-off mass) equals to 0.45 or higher. (By the way, on 9 July 2015 an electric version of Cri-Cri, built by Electravia flew across the English Channel hours before the Airbus E-fun.)

Fig. 10. Cri-Cri, the World smallest twin engine manned aircraft designed by French Colomban (https://en.wikipedia.org/wiki/Colomban_Cri-cri)

All the developing aircraft are planned to support by hybrid propulsion systems, because the technological barriers delaying the full electric aircraft developments. The system is based on a small size gas turbine driving an electric generator. This engine – generator is mounted in central part of the fuselage. Air inlet is at the upper side of the noise (Fig. 11.). The inlet is at upper side too, or at the both lower side of fuselage after gas turbine and commercial load packages. 4 – 8 electrically driven propellers having own small electric motors equip the aircraft. The propellers and their motors are integrated into the wing and they "work" on full span.

The conventional fuselage and cockpit are avoided. The airframe is built from the minimum elements: fuselage as beam truss box with gas turbine – electric energy generator and batteries inside, wings of variable geometry and tail (Fig. 11.)

The control unit is mounted into the "head" of aircraft that is streamlined small body made as independent composite unit.

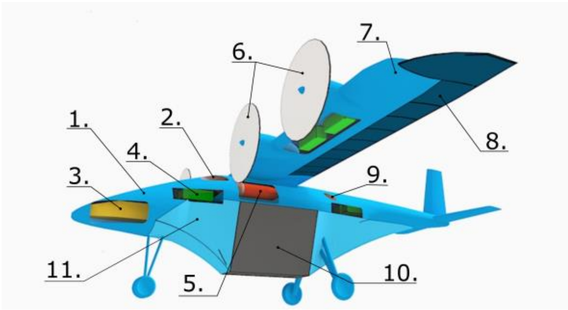

Fig. 11. Layout the developing small cargo UAV with hybrid propulsion system (1.- fuselage, 2.- engine inlet, 3.- control box, 4.- batteries, 5.- gas turbine with electric generator, 6.- propellers, 7.- fix wing, 8.- flexible part of wing, 9.- exhaust gas inlet, 10.- containers, 11.- covering linen)

The carrying containers are fixed to the fuselage beam and they are cover by linen strained by shape-retaining frames.

The wing has one central "rigid" body section holding the individual electric motor driven propellers, too (Fig. 12.). The mean beam is a tube. The fixed wing holds batteries, too.

The variable part of wing is a linen that partly is reeled up on a tube at middle section of wing. The trailing edge is a cable in the linen. This cable is stretched between flexible (and deflectable) tip rod and an electric motor built into the fuselage. It controls the stretching and position of cable. The motor may move back and down for increasing the wing area and the generating extra lift. This is the flap function. The tip rod can be deflected, too, down and up for using the wing tip areas as ailerons.

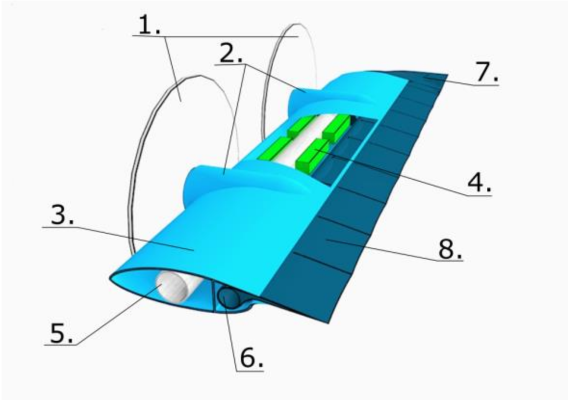

Fig. 12. Principal structure of the wing (1.- propellers, 2.- electric motors, 3.- hard (composite) wing section, 4.- batteries, 5.- beam – tube, 6.- rod rolling the linen, 7.- flexible (composite), deflectable tip rod, 8.- flexible part of wing (linen))

The introduced conceptual design methodology adapted to developing the electric and hybrid aircraft (Fig. 5.) had been applied to development of a smaller version of planned cargo UAV. For reaching the objectives, transferring max 150 kg goods for distance 100 km during 90 minutes, extra constraints were defined:

- the relative empty mass (without the elements of the propulsion system) must not go over 0.2;
- the relative mass of batteries should be less than 10 %;
- the commercial load should be greater than 40 %;
- under 500 m height of flight, the aircraft must use full electric modes;
- the electrification factor must be below 0.2; and
- the power of the aircraft must be enough for recharging, the batteries fully during the cruise flight.

The developed aircraft has the following geometrical characteristics (for case of carrying the 150 kg cargo): length: 4.7 m; wingspan: 7.6 m; wing area: 9.4 m^2; take-off mass: 350 kg, take-off distance: 60 m.

It seems the airfoil selection / design and determination of the wing / aircraft aerodynamic characteristics are the central problems of developing this new, unconventional airplane. The modified (in thickness, camber, positions of maximum thickness and camber) and combination of two different airfoils and specially developing airfoils were studied. The applied solution requires further aerodynamic investigation and development.

The applied unconventional form results to considerable reduced empty weigh of airplanes, but the parasite drag (drag at zero lift) is about 30 – 40 % greater, than the aircraft with analogical weight / size.

The conceptual design methodology (Fig. 5.) results to the following major mass and energy balances (Tables 1. and 2.).

Table 1. Mass balance (mass fractions of total mass) of developed UAV

elements	mass (kg)	mass / MTOW
empty mass (without the propulsion system)	69.8	0.199
gas turbine	21.5	0.061
energy generator	8.2	0.023
fuel system	3.6	0.010
fuel	22.8	0.065
electric system including controllers for batteries	12.2	0.035
batteries	38.7	0.111
4 electric motors	12.8	0.037
4 propellers	10.4	0.030
commercial load	150	0.429
total	350	1.000

Table 2. Energy balance of developed UAV

flight phases	energy (kWh)	electric energy (kWh)	fossil used energy (kWh)	battery mass (kg)	total fuel (l)
taxiing	0.07	0.07		0.29	0.05
take-off (finished at 500 m - that is 4 minutes on P_{max})	3.67	3.67		14.67	2.29
climb to 3000 m (climb rate 3 m/s and 0.9 P_{max})	11.46		11.46		7.16
cruise (altitude 3 km. speed 25 m/s (90 km/h.))	20.32		20.32		12.70
descent	0.00				
approach/landing (from 500 m)	1.80	1.80		7.20	1.13
reserve	12.40	4.13	8.27	16.53	5.17
total	49.72	9.67	40.05	38.69	28.49

The results demonstrate the special, unconventional cargo UAV might be configured and realized.

The project has not finished yet. At first, further investigation is planned for developing and study the airfoil and airplane aerodynamics, structural solutions, stability and control. On the other hand, the developed conceptual design methodology is applying to developing a small 4-seaters airplane, too. The gas turbine – electric energy generator need further study and conceptual design, too. Finally, the up-sizing effects require further studies and evaluations.

5 Conclusions

The future cleaner air transport needs full electric and hybrid aircraft. The available and emerging batteries' technology (because their small specific energy) may not support developing such new aircraft without considerable reduction of flight performance.

The paper recommends using a new approach to conceptual design of the future full electric and hybrid aircraft by introducing additional constraints and increasing the role of mass and energy balances.

By using this new approach and creating original (revolutionary new) solutions the full electric and hybrid aircraft might be developed by applying the existing battery technologies.

The paper demonstrates the applicability of the introduced ideas in developing new methodology for aircraft conceptual design (calculating with some extra constraints defined for aircraft mass and energy balances) and showing results of developing new small cargo UAV with hybrid propulsion system.

The developed cargo UAV airplane families are recommended for use to delivering the fast international shipping and same day parcel delivery systems. These UAVs may apply in remote control modes or in autonomous transport systems.

ACKNOWLEDGEMENT

This work was supported by Hungarian national EFOP-3.6.1-16-2016-00014 project titled by "Investigation and development of the disruptive technologies for e-mobility and their integration into the engineering education".

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