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HYBRID PROPULSION OF MULTI-COPTER TYPE UAVS, FEASIBILITY AND CURRENT STATE OF THE ART

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Abstract

A limiting factor in further development of the electrically driven multicopter type UAVs is their low flight endurance – up to 1 hour with a real payload. It depends, on the limited specific energy of the batteries that multicopters carry on board.One of the solutions to the problem is the use of an energy source with higher specific energy – gasoline. Through it, electricity is generated onboard, which feeds the drive motors and the payload. In theory and in practice, hybrid drives allow the flight endurance of multicopters to reach 4 hours.

Attempts to create multirotor aircraft, powered by internal combustion engines, date back to the beginning of the last century. In general, they are all unsuccessful. The main reason is the inability to manage effectively the thrust of the individual rotors.

The idea of multicopters was successfully implemented about 10 years ago, with the development of unmanned aerial vehicles with electric propulsion (MCP_{ep}).

Nowadays MCP_{ep} are separate, independent and fast growing class in the aviation technique, with good perspectives and application capabilities. They have flight characteristics, robotic and automation potential, with which they are superior to other heavier than air unmanned aerial vehicles – airplanes and helicopters.

The modern MCP_{ep} are powered by propellers with low weight, high aerodynamic efficiency and specific thrust that reach up to 19.0 kg/kW. They are mounted directly on the shafts of brushless electric motors with an efficiency of 95 ÷ 98 % and specific power of 3.0 ÷ 4.0 kW/kg.

The control of MCP_{ep}s flight is carried out by precise and rapid change of the thrust, that create the lifting propellers, via varying of their electric motors *rpm*.

This is done by Electronic speed controllers (ESC), which have efficiency of about 95 % and a relative weight of 0.15 kg/kW.

The MCP_{ep} are mainly powered by lithium-polymer (Li-Po) batteries. At present, they have specific energy (C_pE_c) up to 350 Wh/kg. Their operating life is relatively short – no more than 1 000 charging cycles, while through this time their capacity is constantly decreasing. Their theoretical maximum is 400 Wh/kg. The next generation in the development of lithium batteries is lithium-sulphide (Li–S) and lithium-air (Li-Air) batteries. It is expected their C_pE_c to reach 600 ÷ 1 000 Wh/kg. Now on the market are available Li-S batteries with C_pE_c – 380 Wh/kg. However, they quickly lose their capacity and still have a very limited number of charge-discharge cycles. This makes it difficult to use them for propulsion of MCP_{ep}.

Modern MCP_{ep} are made of composite and other materials with high strength characteristics and low relative weight. Modern technologies are used and effective constructive solutions are being implemented. This allows their empty weight (EW) (with engines and propellers, without batteries and payload (PL) to be reduced to 30.0 ÷ 40.0 %, and the payload to reach 10.0 ÷ 15.0 % of the maximum takeoff weight of the vehicle (MTOW).

The MCP_{ep} fly in high thrust-to-weight ratio. When hovering and maneuvering in calm air they need a thrust (T) that exceeds 1.2 ÷ 1.4 times the MTOW of the vehicle. In dynamic air environment the thrust-to-weight ratio T/MTOW may exceed 2.0. To achieve these parameters, MCP_{ep} must carry on board batteries with high capacity and weight.

The main problem with the modern MCP_{ep} is the limited flight duration (T_{flight}). There are different formulas and electronic calculators for calculating the flight duration of electric driven multicopters. In all of them T_{flight} is a function of the following parameters:

(1) $$T_{flight}. = f(\eta_{pwr}; C_pE_c; C_pT_{prop}; T/MTOW),$$

where: η_{pwr} – efficiency of the electric power transformation (a product from the multiplication of the efficiency of electric motors and controllers ≈ 0.9);

C_pT_{prop} – propeller specific thrust (for existing multiscopers – an average of 11.5 g/W);

T/MTOW – thrust-to-weight ratio 1.4 ÷ 2.0.

The T_{flight} of the multicopter depends mainly on the specific energy of the battery C_pE_c. When using existing lithium-polymer batteries with C_pE_c – 350 Wh/kg, the maximum flight duration of MCP_{ep} with PL (carrying on board a payload representing 10 % of the MTOW) is achieved when the weight of the battery is twice as much as the empty weight of the aircraft. However, it may not be more than 45 minutes (with thrust-to-weight ratio – 1.4), regardless of the MTOW. After this flight duration limit, MCP_{ep} become very heavy, reduces their payload and generally they lose their specific advantages over the airplanes and helicopters.

A solution of the existing problem, while retaining the advantages of the electric propulsion of the lifting propellers, is the generation of electricity on the board of MCP_{ep}, using internal combustion engines – ICE, that work with fossil-type liquid fuels or such, produced from renewable energy sources containing hydrocarbons.

The feasibility of the hybrid propulsion of MCP_{ep} is based on the high specific energy of the widely used liquid fuels, which exceeds many times that of the best batteries. C_pE_c for the diesel and kerosene is about 12 000 Wh/kg. For the gasoline this value is over 12 200 Wh/kg. This is a chemical energy. In order to be used to fuel MCP_{ep} it should be converted into electric. For hybrid propulsion of multicopters, it is best to do this indirectly – using heat engines. In them, the heat produced by the fuel becomes into a mechanical energy that drives power generators.

The specific energy of such a hybrid power plant – $C_pE_cH_y$ depends on the following parameters:

$C_pE_cHy = f(C_pF; \eta_{he}; C_pW_{he}; \eta_{eg}; C_pW_{eg}; C_pE_cB_h)$

C_pF – fuel specific energy – for the gasoline 12 220 Wh/kg;

η_{he} – heat engine efficiency – 5.0 ÷ 45.0 %, depending on type and power range;

C_pW_{he} – specific weight of the thermal engine, exhaust system and control unit 0.450 ÷ 5.0 kg/kW, depending on the type of the engine and power range;

η_{eg} – efficiency of the electric generator, rectifier and control unit ≈ 0.9;

C_pW_{eg} – total specific weight of the electric generator, rectifier and control unit, their cooling system and the connecting node with the heat engine ≈ 1.10 kg/kW;

$C_pE_cB_h$ – specific energy of the Buffer battery – 350 Wh/kg.

The main factors that determine the specific energy of the hybrid power plant are the thermal engine efficiency of and its specific weight. They are vastly dependent on the power, required for the multicopter flight. Modern MCP_{ep} should have a payload of over 2 kg. This means that their MTOW must start at about 20.0 kg. The upper limit on which this type of aircraft loses its advantages is about 50.0 kg (payload – 5 kg). With a specific thrust of the propellers – C_pT_{prop} – an average of 11.5 g/W, the power required by the electric motors is within the range 1.8 ÷ 4.3 kW. Taking into account their efficiency and the efficiency of their power controllers (0.9), a minimum of 2.0 ÷ 4.8 kW should be supplied from the hybrid system. Assuming that the peak loads will be absorbed by the buffer batteries and they provide an average of 5.0 % of the total power (0.1 ÷ 0.24 kW), the capacity of the power generators should be in the range 2.1 ÷ 5.0 kW. With total efficiency of the electric generators, their rectifiers and control blocks ≈ 0.9 – the power of the thermal engines should be 2.3 ÷ 5.5 kW.

For the calculated power range, the most relevant technical specifications have the two-stroke, gasoline internal combustion engines – ICE_{gts}. Their specific weight, fully equipped (with ignition system, exhaust pipe and cooling system) is 1.10 ÷ 1.80 kg/kW, power per liter (80 ÷ 110 kW/dm^3), efficiency (11.0 ÷ 15.0 %).

The dependence between the Brake Thermal Efficiency – BthE – η_{th} and specific fuel consumption – bcfc (g / kW / h) is as follows:

$$\eta_{th} = \frac{100 \times 10^6}{bcfc \times C_pF} \quad ; \quad bcfc = \frac{100 \times 10^6}{\eta_{th} \times C_pF}$$

For ICE_{gts} with η_{th} (11.0 ÷ 15.0 %), the specific fuel consumption – bcfc will be in the range (750.0 ÷ 550.0 g/kWh).

In order to achieve maximum flight duration, a battery powered MCP_{ep} with a maximum take-off weight of 20.0 kg and a payload of 2.0 kg, must have a battery with weight of not less than 10.0 kg. To replace this battery, the hybrid power plant – with the same weight should have a weight:

ICE_{gts} (with power 2.3 kW and efficiency 10 %) with its systems – 2.6 kg;
fuel tank – 3.8 kg (empty – 0.3 kg + fuel – 3.5 kg);
electric generator with rectifier and control unit – 2.4 kg;
buffer battery – 0.4 kg;
supporting structure for mounting the engine, generator and other equipment – 0,8 kg;
total – 10 kg.

With the fuel of 3.5 kg, available on board, the hybrid-powered MCP_{ep} will have flight duration of about 2 hours – more than 2.5 times greater than the maximum possible with batteries. For the above example, the energy density provided by the hybrid power plant – C_pE_cHy is about 1 500 Wh/kg.

The practical realization of the idea of hybrid propulsion of MCP_{ep} starts in 2015. The first multicopter with hybrid drive is the quad-copter HYBRIX.20, Fig. 1. It is created by the Spanish start-up company *Quaternium* based in Valencia. It is assigned to it by the Spanish Ministry of Defense with the Vantex project in the middle of 2015. The same year, in November, a prototype was made and tests began. On December 26, 2017, HYBRIX.20 establishes a flight duration record – a 4 h and 40 min hovering.

Main characteristics of HIBRIX.20:

1. MTOW:	20.0 kg
2. Empty Weight:	13.5 kg
3. Payload:	+ 2.5 kg
4. Flight duration with maximum payload:	2.0 h
5. Cruise speed:	50 km/h
6. Max. speed:	80 km/h
7. Propellers:	30"
8. Operational temperature:	– 10 + 45° C
9. Propulsion system:	hybrid
10. Heat engine:	Two-stroke gasoline ICE
11. Fuel:	Gasoline, 95 octane + 4 oil
12. Batteries:	LiPO 12S

In 2016, after improvements, the maximum payload of the multicopter was increased to 5.0 kg.

HIBRIX.20 is powered by a single cylinder, gasoline, carbureted two-stroke ICE with spark ignition, air cooling and a conventional exhaust system. The shaft of the engine is located horizontally across the longitudinal axis of the multi-copter. By means of an increasing rpm belt drive with a toothed belt and a gear ratio of about 1: 3, it drives a brushless electric motor running in the generator mode. The engine turn over manually, by Pull starter.

Analysis of HIBRIX.20 Flight Duration Results – at full load, with and without payload, show that its engine's specific fuel consumption is around 840 g/kWh. This corresponds to ηth of about 9.6 % and means that this ICE is likely to have a working volume below 30 cc.

With the same aerodynamic configuration as the HIBRIX.20 and with very close flying characteristics is the hybrid quadcopter Tailwind – Fig. 1, developed by the US company *Skyfront*, located in the State of California.

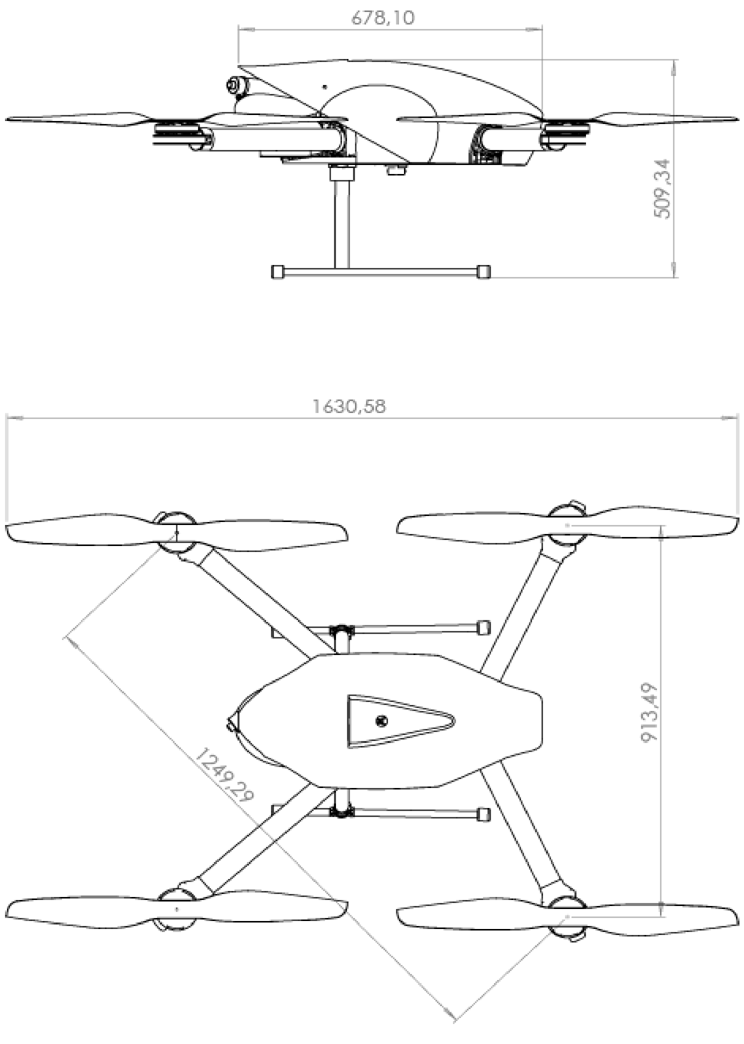

Fig. 1. Main view of HIBRIX.20

Fig. 2. Main view of Tailwind

<u>Main characteristics of *Tailwind*:</u>

1. MTOW:	12.0 kg
2. Payload:	3.0 kg
3. Flight duration with 1.0 kg payload:	3.5 h
4. Flight duration without payload:	4 h 34 min
5. Max. speed:	50 km/h
6. Flight range:	250 km
7. Operational temperature:	0 + 45^{o} C
8. Propulsion system:	hybrid
9. Heat engine:	two-stroke gasoline ICE

The *Tailwind* engine is gasoline, single-cylinder, carbureted. Its shaft is located parallel to the vertical axis of the multi-copter. Its shaft is oriented in parallel to the vertical axis of the multi-copter. It directly drives a three-phase, brushless electric motor that initially starts the ICE and then operates in a generator mode. Fuel consumption of the ICE is about 930 g/kWh. The engine's efficiency is around 8.8 %. Probably it has a working volume of 25 cc.

Chinese company Richen Power has developed a Hybrid Power Plant – NOVA 2000 Generator System H2 – Fig. 3. It is in the form of a separate module for installation into electrically driven multicopters.

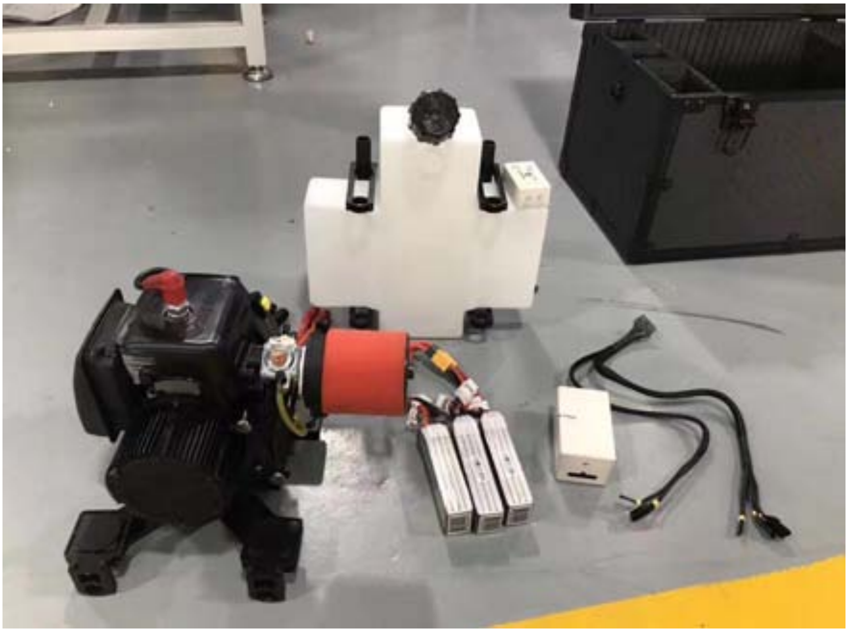

Fig. 3. Main view of NOVA 2000

The engine is two-stroke, gasoline, with carburetor and spark ignition. Its displacement is 32 cc, with a cylinder diameter of 38 mm. The bsfc, depending on the flight regime, is 560 ÷ 750 g/kWh with efficiency 14.6 ÷ 11.0 %. It turns over with an external electric starter. The electric generator is connected to the ICE directly – on one axis. It is three-phase with stationary coils. Its maximum power is 2.0 kW and the nominal – 1.8 kW. The voltage that H2 generates is 48 V. Peak loads in turbulent conditions, when maneuvering and in emergency situations are provided by 3 pcs. LiPo batteries – 1 800 mAh, 75C, 4S. The total weight of the NOVA 2000 Generator System H2, without tank, buffer battery and frame is 5.2 kg. The module is designed to supply with energy quadcopters with total take-off weight up to 18 kg and hexacopters with MTOW – 21 kg.

The NOVA 2000 price is $ 4 660.

GAIA 160 – Hexacopter – Fig. 4 and *Bumblebee* – quadcopter are multi-copter systems with hybrid drive and both are developed by the Chinese company FoxTech. They use NOVA 2000 Generator System H2. The hybrid unit is located under the aircraft along their vertical axis.

Fig. 4. Main view of GAIA 160

The MTOW of GAIA 160 is 19.5 kg. The fuel tank capacity is 6.5 l. With a payload of 2 kg, it provides flight duration of 4 hours. When the payload is 5 kg, GAIA 160's flight duration is 2 h. The maximum flight speed is over 15 m/s. The electric motors are T – MOTOR U8II KV85. The lifting capability of each hexacopter arm is 6.5 kg. This enables GAIA 160 to fly with 5 moto-propeller groups when one of the engines is off.

The GAIA 160 price is $ 20,000.

Chinese company *Guangzhou Walkera Technology* Co. Ltd. uses NOVA 2000 Generator System H2 hybrid module in its hexacopter – QL1200 Gas-Electric Hybrid Drone, Fig. 5.

QL1200 has MTOW of 18 kg at a payload of 3.0 kg. At full load, the flight duration of the multi-copter is 2 h.

Fig. 5. Main view of QL1200

The US company *Top Flight Technologies*, based in Boston, develops the heavyweight *Airborg*™ H8 10K hybrid multi-copter, Fig. 6. It is an 8-rotor quadcopter. On each of the 4 shoulders, coaxial, one above the other are located 2 pcs. electric motors with directly coupled 34" air propellers.

Fig. 6

The multi-copter has the following dimensions: 1 950 mm (L) × 1 600 mm (W) × 1 500 mm (H). It has MTOW of 54 kg and its empty weight is 33 kg (without fuel and payload). At 4 kg payload, its flight duration is 3 h and at 10 kg payload – 1 h. Its maximum speed is 40 mph and the flight range is 100 miles. It can fly at wind speeds up to 35 km/h. The hybrid drive includes a two-stroke, two-cylinder boxer gasoline ICE weighing 7.7 kg and a rated power of 10 kW; Engaged directly to the engine electric starter – generator; fuel tank with a capacity of 19 liters and 50 V, 6 000 mAh, LiPo battery. ICE is mounted under the platform of the multi-copter. Its shaft is directed along the vertical axis of the MCP_{ep}. The generator is above it.

Analysis of flight data of H8, 10K at a payload of 4 kg shows that in this flight regime, the *bsfc* of the ICE is an average of 566 g/kWh – efficiency 14.5 %.

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ХИБРИДНО ЗАДВИЖВАНЕ НА БЕЗПИЛОТНИ ЛЕТАТЕЛНИ АПАРАТИ МУЛТИКОПТЕРЕН ТИП, ОСЪЩЕСТВИМОСТ И АКТУАЛНО СЪСТОЯНИЕ НА ТЕХНИКАТА

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Резюме

Ограничаващ фактор в бъдещото развитие на безпилотните летателни апарати мултикоптерен тип е тяхната ниска продължителност на полета – до 1 час с реален полезен товар. Тя зависи от ограничената специфична енергия на батериите, които мултикоптерите носят на борда си. Едно от решенията на проблема е използването на енергоизточник с по-висока специфична енергия – бензин. Чрез него на борда на мултикоптерите се генерира електроенергия, която захранва задвижващите електродвигатели и полезния товар. На теория и на практика хибридните задвижвания позволяват продължителността на полета на мултикоптерите да достигне 4 часа.