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ANALYSIS OF POSSIBILITIES TO APPLY ELECTRIC TECHNOLOGIES FOR HELICOPTER PROPULSION SYSTEM

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Abstract

Results of analysis related to possibilities to apply electric technologies for helicopter propulsion systems and of progress for several classes of helicopter: super-light, light and medium are presented in the paper. Minimal achievable takeoff mass is estimated, requirements to specific mass of electric devices, providing feasibility and reasonability for implementation of such propulsion system, are defined.

1 Introduction

Now the electrification of air vehicles of different types and mission are considered by manufacturers as one of the most advanced direction of aviation technics development. Using of electrical power has many purposes relating to improvements of technical, environmental, operational performances and other efficiency criteria of air vehicles.

Development of electric vehicle requires comprehensive revision of design principles of its components and systems:

- electric power supply systems (in term of power level, electric parameters such as voltage, current intensity, energy sources and conversion technique, etc.);
- air condition systems, anti-icing systems;
- flight control systems (in term of actuators of flight control, drives of landing gear and pumps of hydraulic system, etc.);
- propulsion systems (in term of thrust generation technics, control systems, oil system, etc.)

Technology support of the development is linked to implementation of adjustable actuators and generators with low specific weight, power sources (batteries, fuel cells with fuel storage and conversion systems), energy converters, etc.

Propulsion system has decisive importance for creation of electric air vehicle. Later on application of electric technologies may lead to revision of propulsion system construction and thrust generation principles.

The estimation of possibilities to apply the electric drive for helicopter propulsion system is a one of the actual problems of electric vehicle development. The application of electro-driven helicopter rotors with variable rotation speed allows of having a set of advantages against existing propulsion systems:

- low required power and mass of propulsion system due to variation of main rotor speed in wide range;
- higher quality of flight trajectory control and improved maneuverability of single rotor helicopter due to possibilities to control rotors rotation speed;
- high reliability and increased engine life due to exception of a number of complex devices (such as gear, transmission, etc.);
- improved maintenance workability (low operational costs);
- high environmental characteristics (low emission, noise);
- improved stealth quality (for military application).

Implementation of the improvements depends on technological capabilities of manufacturing of power sources with required high characteristics, electric and control devices.

At present time works on electrification of a propulsion system (PS) of helicopters are executed by many helicopter and engine engineering companies. The majority of these works are at research and development work stages, some are brought to a stage of demonstrators creation. There is an information on development of such helicopter based on helicopter S-300C by Sikorsky company. At helicopter-demonstrator "Firefly" the piston engine (PE) was replaced by an electric motor of the same power. An energy source is provided by the package of lithium ion batteries.

In 2010 EADS consortium has presented the concept of a hybrid propulsion system for the helicopter with a rotor electric drive. The structure of a hybrid propulsion system for the light helicopter includes two opposed diesel engines with generators, two battaries and unit of power electronics.

Eurocopter company on the basis of single-engine production helicopter AS350 develops the helicopter-demonstrator with the hybrid propulsion system consisting of one gas turbine engine (GTE) and electric motor which is used as reserve only in case of the main engine failure. An electric motor power supply is provided by lithium-polymeric battery.

Electrification works on a propulsion system of the helicopter are being held in CIAM since 2011.

2 Options for propulsion system construction

Herein the following variants of construction of hybrid and electric propulsion systems (fig. 1) are considered:

- a hybrid PS with the electric drive of the tail rotor (the diagram 1);
- a hybrid PS with the electric drive of the tail rotor and with the partial electric drive of the main rotor (the diagram 2);
- a hybrid PS with the electric drive of tail and main rotors with the generative power supply (the diagram 3);
- an electric PS with the electric drive of tail and main rotors with a power supply from the storage battery or from fuel cell (the diagram 4).

The diagram 1. In this diagram GTE or the PE through a gearbox (GB) rotates the main rotor. Electric power generation is carried out by the generator (G), installed on a engine gearbox or built in the engine. Converter (C) transforms alternating current into direct current, which is supplied through the control unit (CU) to the electric motor (EM) of the tail rotor. As the emergency power supply the battery (B) is used.

The diagram 2. In this diagram the drive of the main rotor can simultaneously be carried out from GTE or PE through a gearbox and by means of the electric motor, and a drive of the tail rotor is electric. Electric power development is carried out by generator, which is installed on the traditional engine (GTE or PE). As the

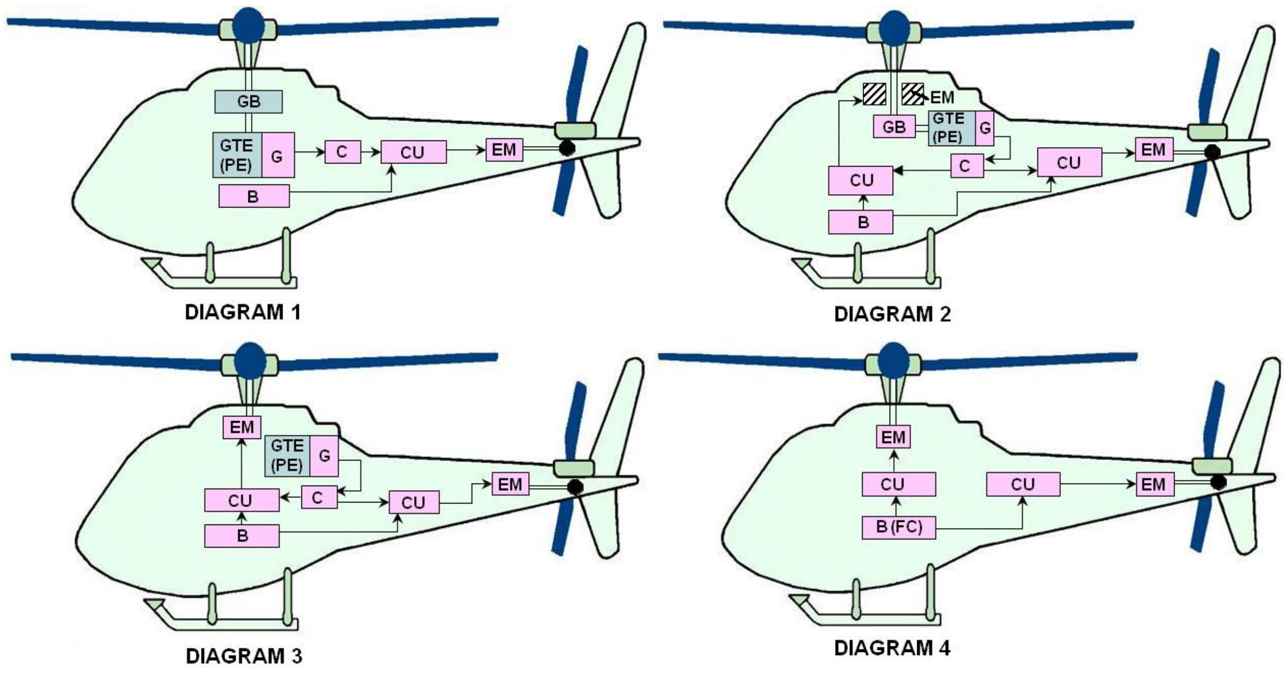

Fig. 1. Variants of electrification of the helicopter propulsion system

emergency power supply the battery is used.

The diagram 3 shows completely electric drive of tail and main rotors. In this scheme electric power generation carry out one or the several generators, installed on the traditional engine (GTE or PE) - the generative scheme. As an emergency energy source the battery is applied.

The diagram 4 shows completely electric propulsion system. In this scheme power supplies of electric motor of tail and main rotors are provided by the battery or a fuel cell (FC).

3 Technique of an estimation of take-off mass of the helicopter

Criterion for an estimation of electrification possibility is the mass of the helicopter at which the defined performance requirements to it can be executed.

The analysis shows, that the mass of components (the engine, auxiliary power unit, transmission, propulsion system, fuel system, etc.) which can be replaced by electric devices, makes from 27 to 40 % from take-off weight of the helicopter of considered types.

At an estimation of achievable take-off weight of helicopters with propulsion system of different type the complex mathematical model of composition of helicopter technical shape was used.

Input data for this model are:

1. A weight category and helicopter application.

The chosen weight categories – super-light, light and medium helicopters. It is accepted, that all three helicopters are intended for a performance of passenger-transport purposes.

2. The basic performance requirements to helicopters (a static ceiling, a dynamic ceiling, the maximum speed of flight, flight range, number of crew, mass of target loading and the equipment).

3. Type and characteristics of the engines (power, specific mass and the specific fuel consumption at the maximum mode).

Reliability of used mathematical model is confirmed by satisfactory convergence of calculation results of the mass balance for existing medium and super-light helicopters. The average error in definition of take-off weight of the helicopter does not exceed 7 %.

4 The analysis of electric device characteristics

Researches and developments of russian and foreign companies show, that electric drives and generators for air vehicles are expedient for developing on base of brushless permanent magnet motors.

In comparison with commutator machines brushless motors have wider regulating range on rotation speed (1:10000 and more), able to operate at 1.5…5 multiple current overload, the best specific indicators, differ simplicity of service. Switched reluctance machines without constant magnets have close characteristics at power less than 5 kW [1, 2].

In the given work for calculation of specific weight the empirical formula is used

$$\gamma = \mathbf{A}\times\mathbf{n}^{-\mathbf{B}}\times\mathbf{N}^{-\mathbf{C}},$$

where **n** – rotation speed, **N** – power, **A** – the factor depending on type of the electric machine cooling (liquid or air), **B** and **C** – approximation factors.

Factors **B** and **C** are defined on brushless motor weight data at power 25…180 kW with rotation speed 2500…53000 rpm. It is accepted, that factors **B** and **C** remain constants in power range 20…600 kW. The calculation error of weight under this formula for known designs does not exceed 10%.

For definition of full brushless electric drive weight to weight of the electric motor it is necessary to add weight of the control unit which makes 30…50% of electric motor weight.

The specific weight of power electronic blocks (converters) is accepted equal 0.3 kg/kW.

In calculations were used achievable at modern technological level values of electric device efficiencies (table 1).

Table 1. Electric device efficiencies

Electric component	Efficiency
Generator	0,96
Converter	0,97
Control unit	0,98
Electric motor	0,93

The specific weight of the electric devices intended for use in vehicle electric propulsion systems, is presented in table 2. Data collation of russian and foreign sources shows that perfection of technologies up to 2020 presumes to reduce specific weight of electric drives, generators and converters approximately twice, batteries in 3…5 times, fuel cells in 3 times comparing to existing level. Cryogenic technologies, which could be applied for cooling (expected to 2030), will allow to lower specific weight of electric drives, generators and converters three times in comparison with present level [2]. By 2030 decrease in specific weight of batteries - in 9 times, fuel cells - in 7 times is possible. Use of superconductivity effect, which allow to lower specific weight of electric devices 10 times, will become possible not earlier than 2050.

Table 2. Electric device specific mass

Component	Specific weight, kg/kW			
	2013 Up-to-date technology	2020 Upgrading technology	2030 Cryogenic technology	2050 Supercon-ductivity technology
Electric drive 20…50 kW >300 kW	0,5…1,0 0,3	0,2	0,1…0,15	0,04
Generator 100…150 kW	0,45	0,25…0,3	0,1	0,03
Converter	0,3	0,15	0,1	0,03
Battery	9,0	1,7	1,0	
Fuel cell	4,75	1,7	0,7	

5 Definition of the electric drive required power

The weight of electric machines depends on their rated power. If power of the electric motor for rotor rotation to define from a condition of its achievement the maximum value in a flight cycle it will lead to unjustified overestimate of a drive weight for following reasons. In a typical flight cycle helicopter rotors operate on a mode of the maximum power within a short term and only on a take-off mode (4 - 7% from flight time), and the rest of the time - on modes with the lowered power. The generalized data for a number of helicopters and engines are resulted in tab. 3, where relative value of used power of the helicopter engine on various flight modes and duration of these modes are resulted.

Table 3. The generalized data on power use for a flight cycle of the helicopter

Behavior		Value
Take-off	Power, %	100
	time, %	4-7
Maximum Continuous	Power, %	75-85
	time, %	46-48
Maximum Cruise	Power, %	55-70
	time, %	45-50

Apparently, the maximum continuous power mode, equal 80 % of take-off power, is used during almost half of the flight time. The power, necessary for a drive of the tail rotor on a hovering, makes 8…10% from take-off engine power. On turn modes this value can increase by 15%. At increase in flight speed the power, consumed by the tail rotor, considerably decreases and practically all engines power is spent for a drive of the main rotor.

At the same time, at definition of required power of a rotor drive it is necessary to consider possibility of short-term overload of the electric motor on value of the torque or a current. For the brushless permanent magnet motor the overload value makes to 2…5 times for the period of 0…3 minutes. Comparing these data with given tab. 3, we see, that the maximum design value of electric drive power can be chosen so that to ensure flight on maximum continuous mode , the longest in a typical flight cycle, and the power, necessary for a take-off mode, it is possible to receive by drive overload on the torque (current).

For main and tail helicopter rotors excess of the required power on a take-off mode in comparison with maximum continuous mode makes 16…25%, and duration of work at a take-off mode does not exceed 5...7 minutes. For the tail rotor electric motor the maximum power exceeds power of a long mode (maximum continuous) not more than for 50 % for the period no more than 1 minute at performance of turns in a hovering and evolutions in flight that is admissible taking into account overload of this drive on a current.

The value of generators required power is chosen considering that they, as a rule, are intended for long work on a rated power mode (close to maximum) and work at factors of an overload 1,1…1,3 within 5 minutes and 1,5…2 within 5 seconds. The value of an admissible overload depends, basically, on a kind of the cooling environment (air, oil, etc.) and speed of it giving to the generator.

6 Estimation of take-off weight

Results of consideration related to possibilities of an application of electric technologies for helicopter propulsion systems and of progress for several classes of helicopters: super-light with take-off weight W_{TO} less than 1500 kg, light with $W_{TO} \leq 6000$ kg and medium with $W_{TO} \leq 25000$ kg are presented on fig. 2. Helicopter take-off mass providing compliance of given specification is selected as main efficiency criteria.

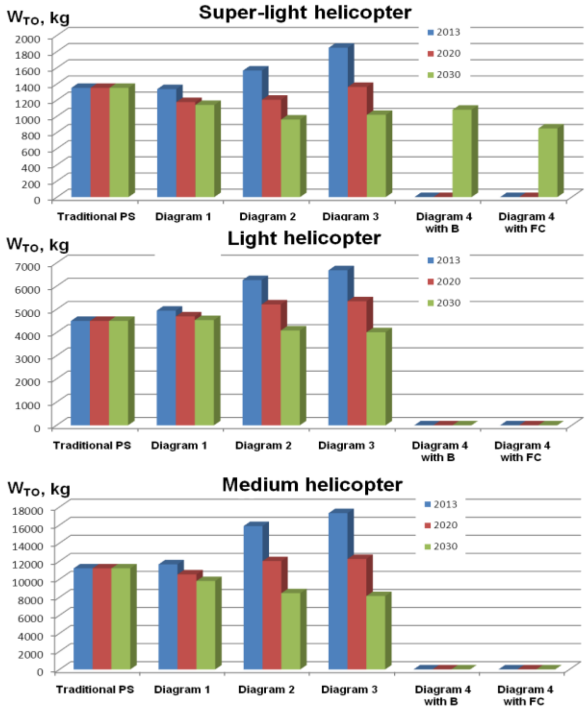

Fig. 2. Results of possibilities of electric technology application in helicopter propulsion systems

In all considered variants of propulsion system electrification of super-light, light and medium helicopters at up-to-date technological level of electric devices the take-off weight of helicopters increases according to fig. 2. The analysis is performed without perfection of weight characteristics of traditional engines.

Exception is application of the construction with the tail rotor electric drive for the super-light helicopter where the weight nearly does not change. That is why it is already reasonable to consider possibilities to apply such propulsion system for super-light and light helicopters due to good opportunities for implementation of mentioned above advantage of electrification at present time.

7 The conclusion

In all considered variants of propulsion system electrification of super-light, light and medium helicopters at up-to-date technological level of electric devices the take-off weight of helicopters increases and construction of completely electric propulsion system (without gas-turbine or piston engine) is unreal because of unacceptable weight increase. Exception is application of the construction with the tail rotor electric drive for the super-light helicopter where the weight almost does not change. That is why it is already reasonable to consider possibilities to apply such propulsion system for super-light and light helicopters due to good opportunities for implementation of mentioned above advantage of electrification at present time.

The helicopter may not be able meet the given specification in case of whole electrification of the propulsion system even for the super-light helicopter using batteries or fuel cells with specific weight predicting for 2020, and its take-off mass may be reduced by 20-40 % (against conventional propulsion system) with specific weight predicting for 2030.

References

[1] Jodeph W. Pratt, Leonard E. Klebanoff, Karina Munoz-Ramos and an. *Proton Exchange Membrane Fuel Cells for Electrical Power Generation On-Board Commercial Airplanes*. Sandia Report, SAND2011-3119, 2011.

[2] Levin A.V., Alekseev I.I., Kharitonov S.A., Kovalev L.K. *Electric aircraft: from idea to implementation*. Mashinostroenie, 2010 (in russian).

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