АВИАЦИОННАЯ И РАКЕТНО-КОСМИЧЕСКАЯ ТЕХНИКА
05.07.01 – Аэродинамика и процессы теплообмена летательных аппаратов;
05.07.02 – Проектирование, конструкция и производство летательных аппаратов;
05.07.03 – Прочность и тепловые режимы летательных аппаратов;
05.07.05 – Тепловые электроракетные двигатели и энергоустановки летательных аппаратов;
05.07.07 – Контроль и испытание летательных аппаратов и их систем;
05.07.09 – Динамика, баллистика, управление движением летательных аппаратов;
05.07.10 – Инновационные технологии в аэрокосмической деятельности

УДК 629.735.45
DOI: 10.26467/2079-0619-2019-22-6-66-74

MULTI-ROTOR HELICOPTER TYPE PLATFORM CAPACITIES RESEARCH

V.I. BUZULUK[1], K.G. KOSUSHKIN[1], V.I. MAVRITSKIY[1]
[1]*Central Aerohydrodynamic Institute, Zhukovsky, Russia*

The development of multi-rotor helicopter concepts, driven by the active introduction of brushless electric motors, leads to the necessity of assessing the multi-rotor scheme main advantages implementing possibility and determining the rational areas of its application. The article analyzes the concept of a multi-rotor platform with a distributed power plant. Parametric study of characteristics depending on the number of rotors for a line of multi-propeller aircraft with take-off weight from 0.5 to 120 tons was carried out. Evaluation of weight and dimensional characteristics of blades, main rotor heads, gear boxes, as well as power wires of electric motors and structure beams connecting the elements of the distributed power plant is obtained. Evaluation of drag and thrust losses on blowing, as well as power requirements for typical flight modes was carried out. Estimation of the required number of rotors for the implementation of the gearless condition and flight safety with one engine failed are obtained. Rational areas of multi-rotor scheme application are defined.

Key words: multi-rotor helicopter, bearing system, distributed power plant, electric engines, drag power.

INTRODUCTION

In order to increase the weight of the cargo, economically lifted by vertical take-off and landing helicopters, it is necessary to increase the rotor disk area. Because of the difficulties connected with the construction of propellers with a very big diameter, the increase of rotor disk area can be reached by constructing multi-rotor bearing systems.

Initially, this possibility was pointed out by N.E. Zhukovsky in his work "About the payload lifted by helicopters" in 1904 [1].

The development of multi-rotor helicopter concept is currently conditioned by the active application of brushless electric engines, with a high specific capacity (up to 5 kW / kg), and lithium-ion batteries. Currently unmanned aircraft with electric or hybrid power plant as well as brushless electric engines with specific capacity up to 0.5 MW are in mass production, which allows us to create aircraft for general aviation and also aircraft for individual use [2]. The advantages of brushless electric engines are realized through reducing the amount of noise and harmful emissions as well as through increasing the reliability and simplification of the design by means of eliminating gearboxes, transmissions, as well as swash plates, due to the separate rotation control of brushless electric engine frequency and main rotor speed.

The use of a distributed power plant architecture which consists of several (usually six or more) electric motors and controllers connected by means of a common tire with backup batteries allows to avoid the problems of sudden engine failure due to the power reserved in the power plant. Engine failure may lead to speed reduction or vice versa, to a climb, but still the absolute control of the aircraft in the operating range is maintained. Improvements in this area are expected to lead to the further reduction in plane crashes.

But the increase in the number of rotors leads to the increase in the dimensions of the units which mount the rotors. The length of the wiring which links the source of electrical energy (battery or electric generators) with the electric engine also changes in case the energy source is located in the fuselage. It is necessary to find a compromise which will be shaped by the particular aircraft performance capabilities layout.

Thus, there is a need to assess the main advantages of implementation possibility and the rational areas of application for a multi-rotor circuit with an electric or hybrid distributed power plant.

METHODS AND METHODOLOGY OF RESEARCH

The research methodology is based on a complex approach to helicopter design, having taken into account the main features of the multi-rotor carrier system. One of the main advantages of the multi-rotor scheme is the increase in load capacity, by means of reducing the total weight of the airscrews and their assemblies, since several airscrews have less weight than one airscrew of the same total area. So, while maintaining the total area of the screws

$$S_\Sigma = n \cdot S_B$$

and increasing their number n the radius of the screws r will be determined through the radius of the original screw unit R, as

$$r = \frac{R}{\sqrt{n}}.$$

The load on the rotor disk area is related to the take-off weight by the following dependence [3]:

$$p = 2,05 \cdot m_0^{0,314},$$

where p is the load on the rotor disk area , kg / m^2, and m_0 is the take-off weight, kg. Thus, having a number of p values, it is possible to determine the corresponding value of m_0 and the area of the propellers S_B.

Taking the number of propellers into account we can calculate the mass of blades, barrels and gearboxes using the engineering methods outlined in [3, 4]. In order to estimate the mass of the structure we analyzed a beam structural-and-power scheme, in which the beams connecting the modules with the main rotor and brushless electric engine work only on bending (figure 1). We examined tubular section beams which are made of fiberglass prepreg adhesive grade KMKS-2M.120. T64 [5] with the wall thickness of 2,5 mm.

One of the characteristic features of helicopter loading is a maneuvering flight which means the helicopter recovery from the planning [6]. In this case, it is considered that the maximum operational overload is $n_{\max}^{э} = 3$; safety coefficient is f =1,5; the number of revolutions of a single main rotor is n = 1,2$(n)_{\text{nom}}$; speed is V = $1,15\ V_{max}$; thrust of the main rotor is $T = n_{\max}^{э} G$; longitudinal force is

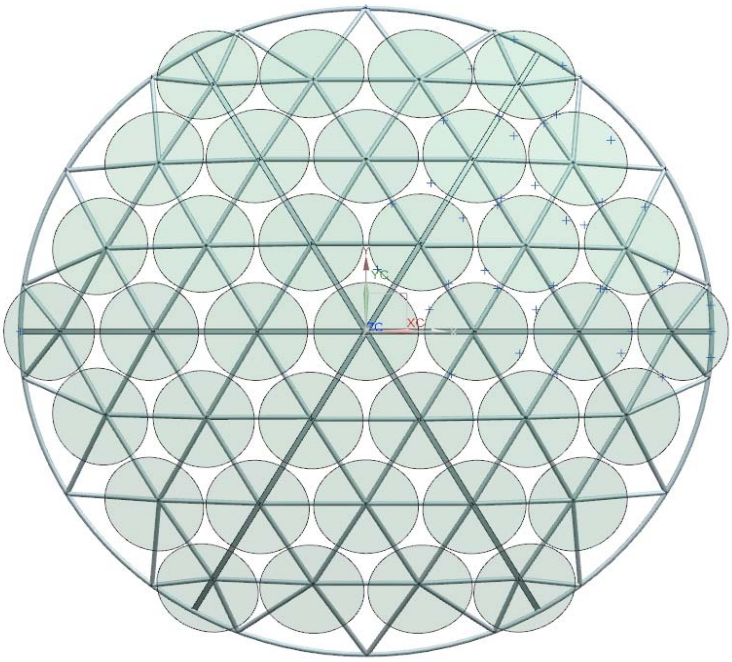

Fig. 1. The multi-rotor bearing system

$H^{Э} = 0{,}15T^{Э}$ and lateral force is $S^{Э} = 0{,}075T^{Э}$. Accordingly, the estimated thrust of each screw was defined as $T_1^{р} = f \cdot n_{\max}^{э} \cdot G/n$.

The main power factor which the frame perceives is the bending moment of $M_{bending}$. Thus, there is tension in the beam:

$$\sigma = \frac{M_{\text{bending}}}{W}.$$

The geometric moment of bending resistance is [7]:

$$W = \frac{\pi}{32} \cdot D^3 \cdot \left[1 - \left(\frac{d}{D}\right)^4\right]$$

where D and d are- outer and inner diameter of the tubular section. So, having known the wall thickness:

$$\delta = D - d,$$

and having the material of the structure, you can calculate the diameter and weight of the beam.

The mass of the beam structure which connects the elements of the distributed power plant (brushless electric engine with main rotor) will be defined by the rigidity requirements in order to eliminate self-oscillations of the rotor on an elastic foundation of the "earth resonance" type. Therefore, when calculating the beam structure, the mass obtained for the case of static loading was multiplied by the weighting coefficient $K_y = 2$.

In order to determine the mass of the motor power wires, based on the structural-and-constructional scheme, we can determine their total length with the different number of main rotors, as well as the thrust and power available for each rotor. It was supposed that the source of electrical energy is located in the fuselage of the aircraft. Besides, it is necessary to determine the required wiring section, which depends on the current amperage and is determined according to electrical standards from the wiring thermal mode operating conditions [8].

For alternating current (AC) lighter wires are required; as the voltage increases, the specific gravity of the wires decreases.

The designed maximum current can be defined as:

$$I_{\max} = \frac{N}{U \times \eta},$$

where N is – the maximum available capacity, η is – the efficiency of the electric engine performance, U_{max} is – the maximum operating voltage. Correspondingly, according to the known characteristics of the electric cables, the cable with the necessary sectional area is selected; the weight of the linear meter cable with polyvinyl chloride and rubber insulation is determined according to the reference table[1].

One of the possible advantages of the multi-rotor scheme is the improvement of flight safety in case of engine failure. In order to assess the feasibility of this advantage, it is necessary to estimate the drag power required for different flight modes, depending on the number of rotors.

The typical flight modes of helicopters are [4]: flying at maximum speed at an altitude of $H = 500\ m$; hovering on a static ceiling; continued take-off when one engine failed and the other one is operating at extreme power; flying on a dynamic ceiling. Each mode has its own parameters of altitude, airspeed, drag power for the main rotor drive and power loss. Thus, the capacity of the helicopter power plant is determined by the maximum value of the flight modes drag power.

Taking into account the interference of rotors in a multi-rotor carrying system the algorithms for calculating drag power, are thoroughly described in works [9, 10].

RESULTS OF THE RESEARCH

Performance predictions of flight characteristics dependency on the number of rotors (from 1 to 120) were made for the family of multi-rotor aircraft with take-off mass from 0.5 t to 120 t and the load on rotor disk area from 15 to 80 kg/m^2. Assessments of weight characteristics for blades and airscrew bosses, gear boxes and electric engines actuators as well as construction beams connecting elements of distributed power plant are given in Figure 2.

When the number of rotors increases, the mass of the construction components connecting the modules of the distributed power plant (main rotor + brushless electric engine) also grows.

The total weight of the beam construction including the weight of rotors, gearboxes and wiring begins to decrease when the number of rotors only for heavy and super heavy aircraft increases at p over 60 kg/m^2 (G_0 over 60 t). At the same time, it should be pointed out that currently the construction of a large diameter propeller and a gearbox for it is a difficult task and presently the largest propeller and gearbox are created for the Mi-26 helicopter with $G_0 = 56\ t$ [11].

Thus, for a number of aircraft under consideration with a G_0 of more than 60 t, the construction of a single-rotor arrangement at a given level of technical perfection is problematic, and therefore it is advisable to use several lifting airscrews.

It should also be noted that for small values of p = 15...30 kg/m^2 with the increased number of screws the wiring makes a significant contribution to the total weight.

---

[1] The hand book of power-engineering constructor. Kiev, 1973. 248 p.

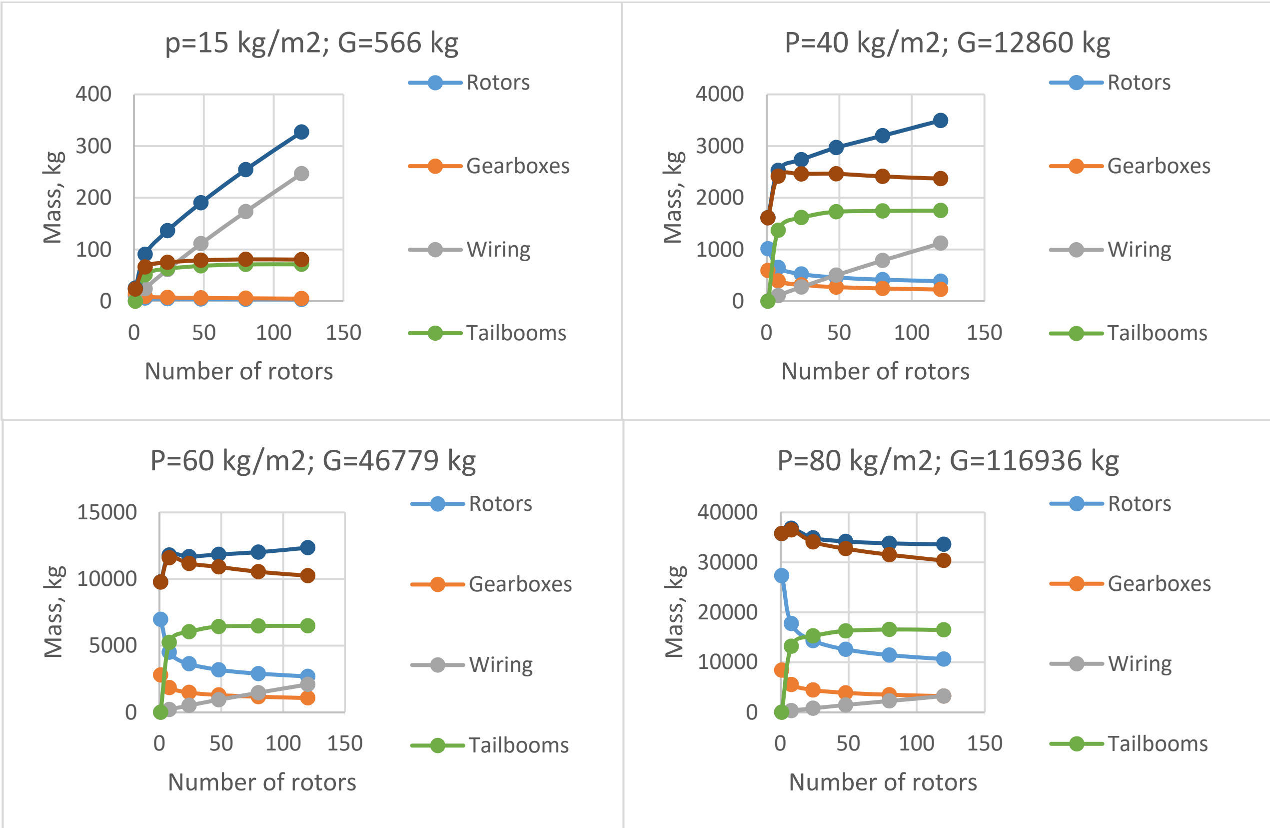

Fig. 2. Main units mass dependency on the number of rotors and take-off mass

One of the advantages of the brushless electric engine operation is the possibility to increase the reliability and the power plant service life by means of simplifying the design of construction and eliminating a number of complex mechanical devices (gearbox, transmission, etc.). In order to exclude the gear box from the scheme of the power plant, we need such type of conformity of the main rotor diameter to the brushless electric engine revolutions that the speed at the ends of the blades did not exceed the critical number of *M*.

As it is shown by the analysis of modern electric engines characteristics [12, 13], the starting number of their rotational speed is mainly 2000 revolutions per minute (rpm). Hence, it can be figured out that the required radius of the main rotor should not exceed 1.2–1.5 m.

Table 1 shows the requirements for the quantity of screws which are necessary for the gearless helicopters with different take-off weight, as well as the possible gain in weight after the refusal of gearboxes.

Table 1

Gear renunciation capability assessment

Rotor disk area loading kg/m^2	Take-off weight kg	The number of screws needed for gear renunciation	Gear box mass
15	566	8…10	10
20	1414	12…15	20
30	5144	30…40	100
40	12860	60	250…270
60	46799	More than 120	1000
80	116936	–	Up to 5500

We can see that in order to renunciate of gearboxes with the increased take-off weight we either need to increase the number of main rotors in case we use ordinary electric engines with speed from 2000 rpm or start using low-speed superconductive electric engines.

Drag power for typical flight modes with different number of propellers are shown in Figure 3.

The Figures show that along with the increase in the number of screws we can see a moderate increase in the drag power necessary for the flight at maximum speed and on the dynamic ceiling, which is due to the increase of drag and to the increase in the number of beams connecting the distributed power plant modules. It should also be noted that with the increase in the number of screws, the drag power needed for hovering on a static ceiling also increases. It happens because of the increase in thrust losses for blowing the increased number of beams.

At the same time, the drag power for the continued take-off mode decreases and its dependence on the number of propellers takes a flat form when the number of propellers n_{prop} is over 14–16. As it can be seen, when the number of propellers is more than 4, the drag power is determined by the hovering mode and has the drag power continued takeoff margin, which admits the failure of more than one engine under the condition of a fully electric distributed power plant or distributed power plant with modules consisting of the main rotor and gas turbine engines, which is more typical for super-heavy multi-propeller helicopter projects. Thus, the flight safety significantly increases, which is especially important when using a multi-rotor scheme with an electric power plant for the aircraft family with a take-off weight of up to 1.5 tons, since the helicopters of this class are usually equipped with only one engine.

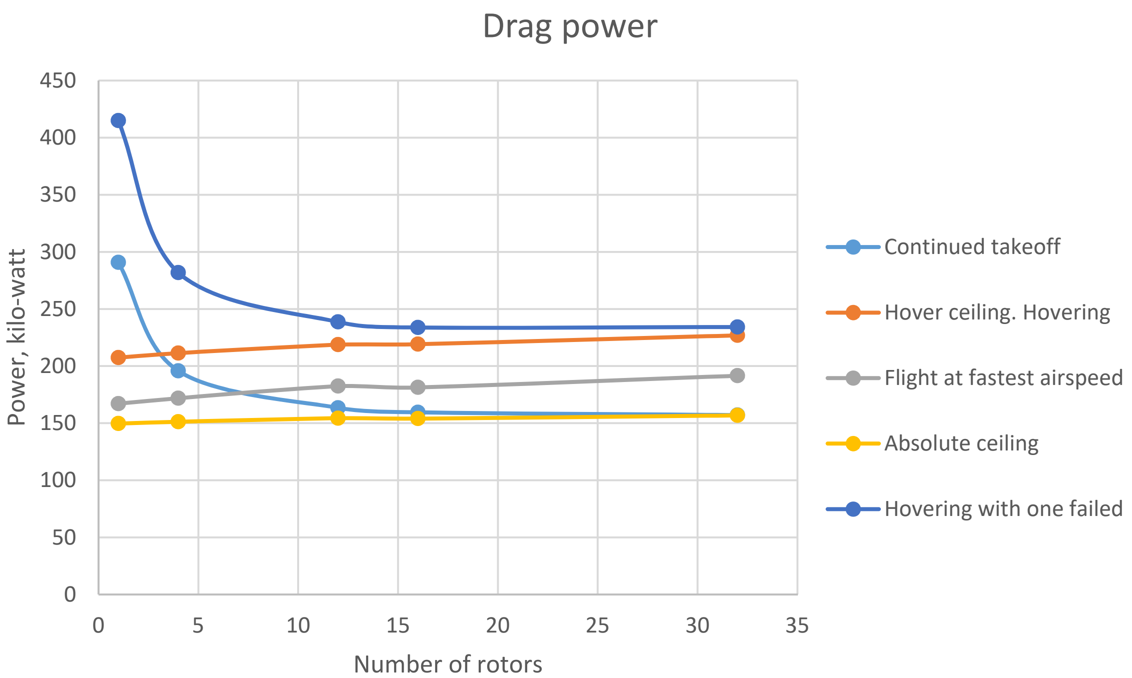

Fig. 3. The drag power at rotor disk loading $p = 40$ kg/m^2

The drag power for the one engine failed hovering mode of flight was also determined and presented in the Figures. The pictures demonstrate that with the increase in the number of rotors over 14–16, the drag power for hovering with one engine failed exceeds the drag power for hovering with all engines running by only 3.5%, which can be very actual for helicopters designed for crane installation work.

CONCLUSION

The analysis of the multi-rotor scheme performance main advantages which was made according to the adopted methodology revealed the following results:

– the increase in the load capacity by reducing the total weight of the main rotors and their assemblies is possible when the take-off weight is more than 60 tons and the rotor disk area is more than 60 kg/m^2, which is appropriate for super-heavy helicopters;

– with the increase in the number of propellers for more than 4, the drag power is determined by the hovering mode and has the drag power continued takeoff margin, which admits the failure of more than one engine under the condition of a fully electric distributed power plant or distributed power plant with modules consisting of the main rotor and gas turbine engines. Thus, the flight safety significantly increases, which is especially important when using a multi-rotor scheme with an electric power plant for the aircraft family with a take-off weight up to 1.5 tons, since the helicopters of this class are usually equipped with only one engine.

– with the increase in the number of rotors over 14–16, the drag power for hovering with one engine failed exceeds the drag power for hovering with all engines running by not more than 3.5%, which can be very relevant for helicopters designed for crane installation work.

Thus, we can conclude that the efficient application areas of a multi-rotor scheme with a distributed power plant are: super-heavy great load capacity helicopters for crane installation work and light helicopters with the load capacity up to 1.5 tons.

REFERENCES

1. **Zhukovsky, N.E.** *O poleznom gruze, podnimaemom gelikopterom* [On the payload lifted by helicopter]. *Vozdukhoplavatel* [Balloonist], 1904, no. 2. (in Russian)

2. **Hepperle, M.** *Electric Flight – Potential and Limitations. Energy Efficient Technologies and Concepts of Operation*, Lisbon, Portugal, 22–24 October 2012.

3. **Kosushkin, K.G. and Mashkova, E.N.** *Razrabotka algoritmov i programy opredeleniya parametrov vertoleta, vypolniayushchego zadannyye trebovaniya po gruzopodemnosti i dalnosti perevozok* [Algorithms and program development for helicopter fulfilling the specific requirements for load capacity and range]. *Materialy XXII nauchno-tekhnicheskoi konferentsii po aerodinamike* [Proceedings of the twelfth scientific and technical conference on aerodynamics]. 2011, p. 89. (in Russian)

4. **Tishchenko, M.N., Nekrasov, A.V. and Radin, A.S.** (1976). *Vertolety. Vubor parametrov pri proektirovanii* [Helicopters. Design parameters selection]. Moscow: *Mashinostroenie*, 366 p. (in Russian)

5. **Dementeva, L.A., Serezhenkov, A.A., Bochareva, L.I., Lukina, N.F., Kutsevich, K.E. and Petrova, A.P.** (2012). *Svoystva kompozitcionnykh materialov na osnove kleevykh prepregov* [Adhesive prepregs composite materials properties]. *Klei. Germetiki. Tekhnologii* [Glues. Sealants. Technologies], no. 6, pp. 19–24. (in Russian)

6. **Voskoboynik, M.S., Lagosyuk, G.S., Milenkiy, Yu.D., Mirtov, K.D., Chernenko, Zh.S., Osokin, D.P., Skripka, M.L. and Ushakov, V.S.** (1972). *Konstruktsiya I prochnost samoletov I vertoletov* [Aircraft and helicopters constructional strength], in Mirtov K.D. and Chernenko Zh.S. (Ed.). Moscow: Transport, 440 p. (in Russian)

7. **Shalashilin, V.I., Gorshkov, A.G. and Troshin, V.N.** (2000). *Soprotivlenie materialov* [Materials resistance]. Moscow: Izdatelstvo MAI, 615 p. (in Russian)

8. **Kosushkin, K.G. and Mavritsky, V.I.** (2017). *Razrabotka kontseptsii mnogovintovoy platformy s raspredelennoy silovoy ustanovkoy* [The distributed power plant multiple platform concept

development]. *Materialy XXVII nauchno-tekhnicheskoikonferentsii po aerodinamike* [Proceedings of the twelfth scientific and technical conference on aerodynamics], pp.149–150. (in Russian)

9. Vildgrube, L.S. *(*1977). *Vertolety. Raschet integralnykh aerodinamicheskikh kharakteristik i letno-tekhnicheskikh dannykh* [Helicopters. Integral aerodynamic characteristics and flight performance data calculation]. Moscow: Mashinostroenie, 152 p. (in Russian)

10. Yuryev, B.N. (1961). *Vozdushnyye vinty. Vertolety: Izbrannyye Trudy* [Aircraft propellers. Helicopters. Selected Works]. Moscow: *Izdatelstvo Academii Nauk SSSR*, vol. 1, 553 p. (in Russian)

11. Mikheyev, V.P. (1998). MIL Moscow Helicopter Plant, 50 Years. Moscow: Lyubimaya Kniga, 272 p.

12. Frank, A. (2018). *Hybrid-electric propulsion systems for aircraft. Siemens AG eAircraft*. Electric & hybrid aerospace technology symposium, Cologne, November 8th, 2018.

13. Anghel, C. (2015) *Hybrid electric propulsion technologies 1mw high efficiency generator*. Technology Fellow, Oct 18, 2015.

INFORMATION ABOUT THE AUTHORS

Valentin I. Buzuluk, Doctor of Technical Sciences, Head of Research Department Division № 10, Central Aerohydrodynamic Institute, vbuzuluk@yandex.ru.

Konstantin G. Kosushkin, Head of Research Department Sector № 10, Central Aerohydrodynamic Institute, kostinen@mail.ru.

Vladimir I. Mavritsky, Candidate of Technical Sciences, Research Department № 10 Chief Research Engineer, Central Aerohydrodynamic Institute, mavritsky@tsagi.ru.

ИССЛЕДОВАНИЕ ВОЗМОЖНОСТЕЙ МНОГОВИНТОВОЙ ПЛАТФОРМЫ ВЕРТОЛЕТНОГО ТИПА

В.И. Бузулук[1], К.Г. Косушкин[1], В.И. Маврицкий[1]
[1]*Центральный аэрогидродинамический институт имени профессора Н.Е. Жуковского, г. Жуковский, Россия*

Развитие концепций многовинтовых вертолетов, обусловленное активным внедрением бесколлекторных электрических двигателей, приводит к необходимости оценки возможности реализации основных достоинств многовинтовой схемы и определения рациональных областей ее применения. В работе проведен анализ концепции многовинтовой платформы с распределенной силовой установкой. Для линейки многовинтовых летательных аппаратов с взлетной массой от 0,5 до 120 т проведено параметрическое исследование характеристик в зависимости от числа несущих винтов. Получены оценки весовых и габаритных характеристик лопастей и втулок несущих винтов, редукторов, а также проводов питания электрических двигателей и балок конструкции, соединяющей элементы распределенной силовой установки. Проведены оценки лобового сопротивления и потерь тяги на обдувку, а также потребных мощностей для характерных режимов полета. Получены оценки потребного числа несущих винтов для реализации условия безредукторности и безопасности полета с одним отказавшим двигателем. Определены рациональные области применения многовинтовой схемы.

Ключевые слова: многовинтовой вертолет, несущая система, распределенная силовая установка, электрические двигатели, потребная и располагаемая мощность.

СПИСОК ЛИТЕРАТУРЫ

1. Жуковский Н.Е. О полезном грузе, поднимаемом геликоптером // Воздухоплаватель. 1904. № 2.

2. Hepperle M. Electric Flight – Potential and Limitations. Energy Efficient Technologies and Concepts of Operation, 22–24 October 2012, Lisbon, Portugal.

3. **Косушкин К.Г., Машкова Е.Н.** Разработка алгоритмов и программы определения параметров вертолета, выполняющего заданные требования по грузоподъемности и дальности перевозок // Материалы XXII научно-технической конференции по аэродинамике. Центральный аэрогидродинамический институт им. проф. Н.Е. Жуковского, 2011. С. 89.

4. **Тищенко М.Н., Некрасов А.В., Радин А.С.** Вертолеты. Выбор параметров при проектировании. М.: Машиностроение, 1976. 366 с.

5. **Дементьева Л.А.** Свойства композиционных материалов на основе клеевых препрегов / А.А. Сережников, Л.И. Бочарова, Н.Ф.Лукина, К.Е. Куцевич, А.П. Петров // Клеи. Герметики. Технологии. 2012. №6. С 19-24.

6. **Воскобойник М.С.** Конструкция и прочность самолетов и вертолетов / Г.С. Лагосюк, Ю.Д. Миленький, К.Д. Миртов, Ж.С. Черненко, Д.П. Осокин, М.Л. Скрипка, В.С.Ушаков / Под ред. проф. К.Д. Миртова, Ж.С. Черненко. М.: Транспорт, 1972. 440 с.

7. **Шалашилин В.И., Горшков А.Г., Трошин В.Н.,** Сопротивление материалов. М: Издательство МАИ, 2000. 615 с.

8. **Косушкин К.Г., Маврицкий В.И.,** Разработка концепции многовинтовой платформы с распределенной силовой установкой // Материалы XXVIII научно-технической конференции по аэродинамике. Центральный аэрогидродинамический институт им. проф. Н.Е. Жуковского. 2017. С. 149–150.

9. **Вильдгрубе Л.С.** Вертолеты. Расчет интегральных аэродинамических характеристик и летно-технических данных. М.: «Машиностроение», 1977. 152 с.

10. **Юрьев Б.Н.** Воздушные винты. Вертолеты: избранные труды. М.: Издательство Академии наук СССР, 1961. Т. I. 553 с.

11. **Михеев В.Р.** МВЗ им. М.Л. Миля 50 лет. М.: «Любимая книга», 1998. 272 с.

12. **Frank A**. Hybrid-electric propulsion systems for aircraft. Siemens AG eAircraft // Electric & hybrid aerospace technology symposium, Cologne, November 8th, 2018.

13. **Anghel, C.** Hybrid electric propulsion technologies 1mw high efficiency generator // Technology Fellow, Oct 18 2015.

СВЕДЕНИЯ ОБ АВТОРАХ

Бузулук Валентин Иванович, доктор технических наук, начальник отдела научно-исследовательского отделения № 10 ФГУП ЦАГИ, vbuzuluk@yandex.ru.

Косушкин Константин Геннадьевич, начальник сектора научно-исследовательского отделения № 10 ФГУП ЦАГИ, kostinen@mail.ru.

Маврицкий Владимир Иванович, кандидат технических наук, главный научный сотрудник научно-исследовательского отделения № 10 ФГУП ЦАГИ, mavritsky@tsagi.ru.

Поступила в редакцию	24.06.2019	Received	24.06.2019
Принята в печать	14.11.2019	Accepted for publication	14.11.2019