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ANALYSIS OF MASS-ENERGY BALANCE OF UNMANNED AIRCRAFT FUELED BY SOLAR ENERGY

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Визначені принципи забезпечення живленням систем літака на всіх режимах польоту. Описані фактори, що впливають на продуктивність роботи сонячних панелей літака. Запропоновано модель для визначення маси літака вцілому, яка враховує масові характеристики промислових складових літального апарату. Отримано розрахункову модель масово-енергетичного балансу літака з урахуванням типових режимів польоту та законів генерації енергії сонця

Ключові слова: масово-енергетичний баланс, літак на сонячній енергії, умови реалізації польоту

Определены принципы обеспечения питанием систем самолета на всех режимах полета. Описаны факторы, влияющие на производительность работы солнечных панелей самолета. Предложена модель для определения массы самолета в целом, которая учитывает массовые характеристики промышленных составляющих летательного аппарата. Получена расчетная модель массово-энергетического баланса самолета на основе типовых режимов полета и законов генерации энергии солнца

Ключевые слова: массово-энергетический баланс, самолет на солнечной энергии, условия реализации полета

1. Introduction

Thanks to technical progress, today there is an opportunity to perform long flights using solar energy. Despite significant energy capacities of solar radiation, the efficiency of its conversion into translational motion of an aircraft largely depends on the mass-energy characteristics of photoelectric converters. In addition, this process is significantly influenced by the characteristics of power accumulation, the power plant, control systems and parameters of aerodynamic and structural perfection of the aircraft frame.

The relevance of the work lies in increasing efficiency of the process of designing aircraft, fueled by solar energy, by establishing relationships between energy and mass factors. The problem of rational synthesis of parameters of an aircraft is multi-criterial and requires deep analysis.

On the one hand, minimizing the weight of the structure is a priority task. On the other hand, provision of sufficient power to perform a flight dictates requirements for geometric and weight characteristics of an aircraft. As a result, there occurs the problem of uncertainty, which is global in nature.

2. Literature review and problem statement

The problem of the implementation of flight of an aircraft, fueled by solar energy, receives serious attention of scientists all over the world. Thus, paper [1] presents an analysis of the present state of research into the subject matter of aircraft, fueled by solar energy. The problems that occur when creating the aircraft of this type and the recommendations for their solution are described. Certain technological aspects in the aircraft design are highlighted.

The methods of power generation and energy saving aboard an aircraft are described in paper [2]. However, the peculiarities of choosing power parameters (specific power of propulsion, power of the solar plant) of an aircraft were not revealed in full.

Articles [3, 4] present assessment of operation of the power supply system of an aircraft based on lithium-sulfur battery and solar cells. An analysis of the principles of power saving for the realization of long-haul flights and potential power sources was conducted. As lithium-sulfur batteries have a limited resource (50-60 cycles) and are not sufficiently represented in the market, it is not expedient to consider them as the basic power batteries. The authors did not explore the structural constraints imposed on an aircraft when using the solar cells.

In paper [5], authors conducted an analysis of the energy balance of an aircraft, fueled by solar power, based on the use of photogalvanic system and hydrogen batteries. Despite their high efficiency, hydrogen batteries have significant weight and size limitations and significant costs, which results in difficulties when creating a serial, economically efficient unmanned aircraft. It should be noted that the established dependences between the weight geometrical and power parameters are defined for particular aircraft prototypes. The obtained results are not universal for other aircraft, fueled by solar energy.

In articles [6, 7], the specific features of operation of solar power plant aboard an aircraft are described. The factors that reduce efficiency of solar panels operation were distinguished. The authors presented an analysis of the fall of the solar radiation on aerodynamic surfaces of an aircraft, together with a full model of the calculation of total solar radiation that falls on the aerodynamic profile during a cruise flight. Requirements for the selection of a wing profile were formulated. In contrast, the specifics of calculation of total solar radiation at the stage of a flight, which are different from those of a cruise (horizontal) flight, were not revealed. The relationships between geometric characteristics and other aircraft parameters were not described.

In [8], the equation of existence of an aircraft, fueled by solar power, was formed based on the synthesis of the laws of aerodynamics and the conditions of its energy balance. However, an analysis of the influence of power, geometric and aerodynamic characteristics of weight parameters of an aircraft was not performed in the paper.

Article [9] substantiated a general approach to determining the basic parameters of the wing of a plane, fueled by solar energy, and developed the calculation algorithm. Despite the fact that the wing of an aircraft is the main unit, it is necessary when creating an aircraft to have a general approach on defining the design parameters of an aircraft as a whole.

Therefore, the features of implementing a flight of an aircraft, fueled by solar energy, were fairly well researched. However, the principles of aircraft power supply are described mostly for a cruising, horizontal flight. Information about aircraft power supply at the stages different from the horizontal flight is insufficiently highlighted, especially for power consuming modes (take-off, gaining altitude). There is no a general analytical model of the mass-energy balance. There are no data on the possibilities of building an aircraft based on low-cost industrial components.

3. The aim and tasks of research

The aim of present work is to create a mass-energy model of an airplane, fueled by solar energy, taking into account the standard modes of flight and the laws of solar energy generation. This will make it possible, at the stage of outline designing, to improve the process of predicting the characteristics of unmanned aircraft, fueled by solar energy.

To achieve the set aim, the following tasks had to be solved:

– to determine the power required for the implementation of a horizontal flight;

– to establish the total power consumption for performing a flight, including take-off and maneuvers;

– to establish the amount of power generated during a flight;

– to describe principles for predicting the magnitude of the total take-off weight of an aircraft.

4. Materials and methods of research into features to provide for the mass-energy balance

4. 1. Methods for the realization of mass-energy balance

In contrast to previous studies, we consider the possibility of performing an aircraft flight at the altitudes of up to 3000 meters, using the commercially available solar cells as photoconverters [8]. In addition, we set the task of examining the conditions of performing not only a horizontal flight, but also the modes that require provision of additional power consumption. These modes include performing maneuvers, take-off/landing, flying in heavy clouds/shading, flying at dusk, etc. To understand the characteristics and principles of creating an aircraft of this class, it is necessary to consider in detail the basics of providing mass-energy balance and its specificity.

In this case, for the implementation of a flight, it is necessary to provide certain conditions: mass and energy balance.

Mass balance, which is the lifting force obtained on aerodynamic surfaces, must equal the total weight of the constituent parts of an aircraft. Energy balance, which is the energy required for a flight implementation, should not exceed the existing energy (generated solely by solar panels, or in combination with the battery power). The given concepts are quite complex, multi-criterial and exist in close interrelation with each other. The degree of interaction is defined by the typical task (TT) for an aircraft, which is typically formed jointly with the customer. Based on the above, the mass-energy balance of an aircraft, fueled by solar energy, may be represented in the form of the schematic, shown in Fig. 1.

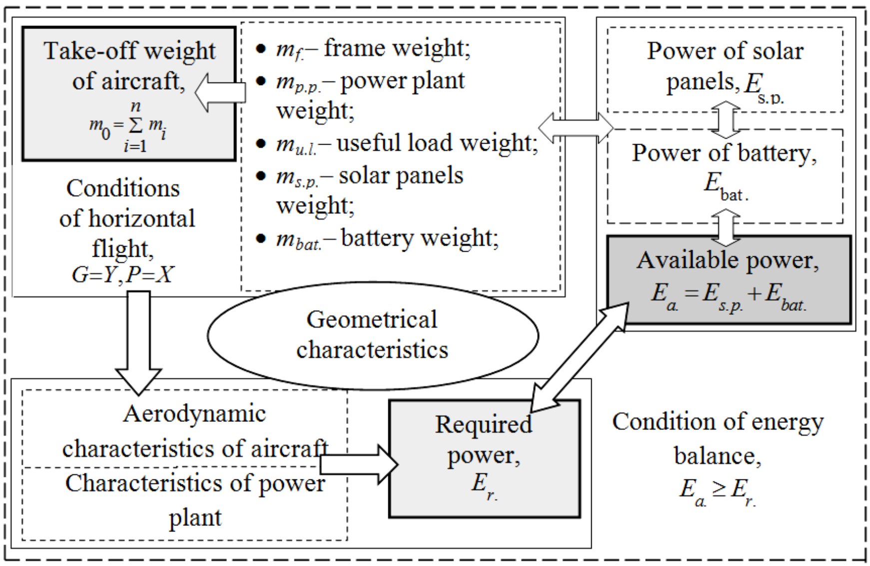

Fig. 1. Schematic of the mass-energy balance of an airplane, fueled by solar energy: X, Y are the magnitudes of lifting force and aerodynamic resistance; P is the thrust of propeller; G is the force of gravity acting an aircraft

There are two possible variants of implementation of the scheme of balance, presented in Fig. 1 [10]:

– *by the discrete method*, which implies preliminary choice of the aircraft's components (engine, solar panels, etc.) based on the estimated calculation of the required power, considering the experience, analysis of similar structures and characteristics of the early prototypes. In this case, if we know the weight of the aircraft's components, it is possible to define the preliminary geometry of an aircraft and its take-off weight. By predicting the required power for a flight implementation, we can make choice on the propeller-engine couple and provide the required power with a set of a certain number of solar cells;

– *by the analytical method*, which implies establishing an array of relationships between the aircraft's components with a description of analytical equations and using mathematical models of each component and an aircraft as a whole.

Since the analytical method is more objective and unified, it is worth choosing it as the basis. However, some correlations between the parameters of a plane are difficult, and in some cases impossible, to describe analytically, so in order to select the parameters of an aircraft, it is necessary to combine the advantages of both methods.

4. 2. Mathematical modeling of relationships between the main parameters of an aircraft, fueled by solar energy

To create a mathematical model that describes interrelations between the main parameters of a plane, fueled by solar energy, it is proposed to describe the main constutuents by stages. In particular:

– power, required for the implementation of a horizontal flight;

– total power consumption for performing a flight, including take-off and maneuvers;

– magnitude of power, generated during a flight;

– total take-off aircraft weight.

To obtain the total weight of an aircraft and its further use, it is necessary to develop a mass model of an aircraft and each of its components. These include the weight constants, weight of aircraft structures, weight of solar panels, weight of the block of controlling the maximum power point, weight of battery, and weight of power plant.

4. 3. Experimental research

In order to conduct verification results of research, several experimental samples of the aircraft, fueled by solar energy, were fabricated, Fig. 2, *a, b*.

In the process of their design, the devised mass-energy model (Fig. 6) was tested for determining the parameters of an aircraft. Verification was carried out by conducting a series of flights with registering the data on the operation of the solar power plant and the systems of an aircraft. The flights were carried out for different configurations of aircraft and weather conditions. The aircraft's weight (3–5 kg), adjustment of the control system, power plant characteristics (36–98 W) were varied. A change in the required and generated power for various flight stages was determined.

a

b

Fig. 2. Experimental samples of the aircraft, fueled by solar energy: *a* – experimental sample of a two-beam scheme with polycrystalline solar panels; *b* – experimental sample with monocrystalline solar panels

5. Results of research into provision of mass-energy balance of an aircraft fueled by solar energy

5. 1. Power for a horizontal flight

During a steady horizontal flight, the lifting force, created by the wing, balances the aircraft's weight, and the thrust, generated by the propeller, balances the forces of aerodynamic resistance. The given conditions may be represented by equations (1), (2):

$$G = Y = C_Y \frac{\rho V^2}{2} S, \tag{1}$$

$$P = X = C_X \frac{\rho V^2}{2} S, \tag{2}$$

where C_Y, C_X are the coefficients of lifting force and aerodynamic resistance; $\rho V^2/2$ is the velocity head; S is the area of a wing.

Accordingly, the value of power N, necessary for the implementation of a steady horizontal flight, taking into account that the area of a wing is associated with elongation λ and span l ($\lambda = l^2/2$), is equal to:

$$N = X \times V = \frac{C_X}{C_Y^{3/2}} \frac{m_0^{3/2}}{l} \sqrt{\frac{2\lambda g^3}{\rho}}. \tag{3}$$

Given the actual technical capacities, taking into account dependence (3), the energy balance of an aircraft, fueled by solar energy, can be implemented at low flight velocities, low wing loading and high aerodynamic perfection.

5. 2. Calculation of the required power

In the first approximation, a horizontal flight is realized using the power of solar panels. In a simplified case, total electric power consumption $P_{t.}$ is equal to:

$$P_{t.} = N, \tag{4}$$

however, given the existence of other consumers aboard the aircraft, we obtain:

$$P_{t.} = N + P', \tag{5}$$

where p′ is the power consumption of various components of a flight.

In addition, while calculating N, it is necessary to take into account the characteristics of constituent elements of the aircraft power plant: efficiency of electric engine, its electronic controller, a gearbox (if any), a propeller [8, 10, 11]. In turn, we should decompose p′ as the total of power consumption of the control system (autopilot, electric drives, navigation devices, communication, controlling and measuring devices, etc.) and a useful load. Since power supply parameters for the control system and useful load are significantly different from power supply parameters for the engine, it is necessary to consider availability of voltage converters in the power supply system. Summing up the above, we may derive an equation of the total required electric power:

$$P_{t.} = \frac{1}{\eta_{e.e.} \times \eta_{e.c.e.} \times \eta_{g.} \times \eta_{p.}} N' + \frac{1}{\eta_{v.c.}} \left(P_{c.s.} + P_{u.l.} \right), \tag{6}$$

where $\eta_{e.e.}$ is the effectiveness of the electric engine; $\eta_{e.c.e.}$ is the effectiveness of electronic controller of the engine; $\eta_{g.}$ is the gearbox effectiveness; $\eta_{p.}$ is the propeller effectiveness; $\eta_{v.c.}$ is the effectiveness of voltage converters; $P_{c.s.}$ is the power consumption of control system; $P_{u.l.}$ is the power consumption of useful loading; N' is the actual power plant capacity.

To obtain magnitude $E_{r.}$, it is worth summing up power consumption under all modes of plane flight:

$$E_{r.} = E_{h.f.} + E_{m_1} + E_{m_2} + \ldots + E_{m_m}, \tag{7}$$

where $E_{h.f.}$ is the power for a horizontal flight, E_{m1}, E_{m2}, E_{mm} are the power for performing maneuvers, m is the maneuver number.

When calculating the total power $E_{r.}$, required for the flight performance, it is necessary to consider, in addition to the total consumed energy:

– existence of a battery, and therefore, its effectiveness at charging/discharging;

– existence of flight modes, under which the deficit of the current generated power occurs.

The flight modes, which result in a deficit, include cloudiness/shading, twilight, etc. The battery is required for the accumulation of excessive generated power and the compensation of power deficit.

It is proposed, for a generalized case of flight, to represent energy consumption as a share ratio to power consumption at a horizontal flight. To determine possible power consumption under the modes other than a horizontal flight, we shall introduce a coefficient, which takes into account a change in the required power – k(α, β, γ). In this case, we have:

$$E_{r.} = P_{t.} \times \left[T_{h.f.} + \sum_{i=1}^{m} k\left(\alpha, \beta, \gamma\right) \frac{T_{mi}}{\eta_{char} \eta_{dischar}} \right], \ i = 1 \ldots m, \tag{8}$$

where $T_{h.f.}$ is the time of a horizontal flight; T_{fi} is the time of maneuver performance; $\eta_{char.}$, $\eta_{dischar}$ are the effectiveness of battery charging/discharging; α, β, γ are the angles of pitch, roll, and yaw, respectively.

Equation (8) allows us to determine power consumption for any stage or a flight mode. For example, for a take-off: roll and yaw angles take zero values, there is no surplus of the generated power. The battery is not charged. The battery is included in the power supply system. As a result, we obtain:

$$E_{take-off} = P_{r.} \times k\left(\alpha\right) \frac{T_{take-off}}{\eta_{dischar}}, \tag{9}$$

where k(α) is the coefficient that takes into account an increase in the required power at take-off; $E_{take-off}$ is the power consumption at the take-off stage; $T_{take-off}$ is the take-off time.

In reality, when performing a flight, there are conditions, under which the power, obtained from solar panels, becomes insufficient, for example:

– at performing a maneuver, the magnitude of the required thrust increases. The required power becomes larger than the total power of solar panels. In addition, the orientation of solar panels relative to the Sun could change causing a decrease in their capacity;

– when the shading phenomenon occurs, caused by cloudiness or by other factors, the solar panels power decreases;

– in dusk and at dawn, the solar radiation level is lower, the power of aircraft solar panels is lower than the total required capacity.

It is obvious that in these situations it is necessary to use both sources, that is, solar panels and a battery. The degree of contribution of each source to the formation of total required power is different, while the process is dynamic, progressive and requires special studies. Accordingly, there is a necessity to refine the dependences (8), (9).

5. 3. Solar radiation. Calculation of generated power

The solar radiation intensity depends on many variables such as geographical location, time, spatial orientation, weather conditions and the magnitude of radiation reflected from the Earth's surface. To determine the magnitude of insolated energy, we used a twoparametric model, which includes the magnitude of maximum radiation $P_{rad..max.}$ and flight duration $T_{n.}$ [12]. Taking the city of Kyiv as an example, Fig. 3 shows the distribution of solar radiation over 24 hours. To take into account the cloudy days, it is proposed to introduce a factor η_{prop}. It varies by value in the range from 1 – clean sky and 0 – total cloudiness, and is experimentally determined according to the international cloudiness classification [13].

The influx of solar energy per square meter during flight E_f is defined as the area under the curve (Fig. 3) and can be calculated from dependences (10), (11):

$$E_f = \eta_{prop.} \frac{2P_{rad.max.} T_{n.}}{\pi}. \qquad (10)$$

However, in the integral from:

$$E_f = \eta_{prop.} \int_{t_{take-off}}^{t_{landing}} P_{rad.}(T) dT. \qquad (11)$$

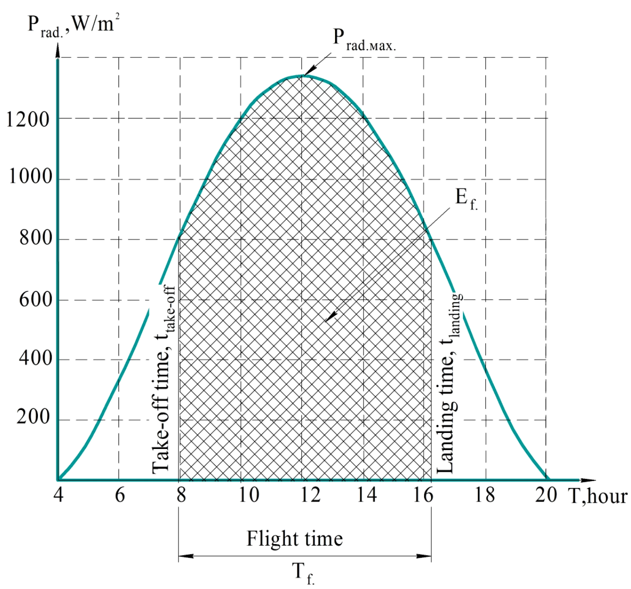

Fig. 3. Distribution of solar radiation over a light day in June for the city of Kyiv: $P_{rad.}$ is the magnitude of solar radiation; T is the time of day

In wintertime, the duration of day and radiation intensity decrease due to the appropriate orientation of the Earth relative to the Sun. Therefore, in summer, it is easier to enable a continuous aircraft flight. The solar radiation intensity directly depends on the geographic location. Near the equator, the radiation intensity is the highest, while at the poles it is the lowest. In addition, the duration of solar day on the equator is constant. Therefore, the total amount of received solar energy is maximal and more constant over a year.

The total electrical power, received by the panels over the flight time, can be determined by multiplying the result of equation (10) by the area of solar panels, their efficiency and performance efficiency of the unit of tracking the maximum power point. In addition, it should be noted that solar panels are not located on the horizontal plane but rather on the surface that is formed by the upper derivative of aerodynamic profile. With uneven illumination, the shaded areas of solar panels exert a negative effect on the performance of the rest of solar cells, limiting the operating capacity of the flow. This problem is especially noticeable in a flight execution at sunrise/sunset and in winter, when the Sun's height is low. Not less important is the orientation of aircraft relative to the Sun and the geometry of a wing, the aircraft assembly. Schematically described features are partially shown in Fig. 4, *a–f*, taking four solar cells as an example:

– at takeoff/landing (Fig. 4, *a, b*), the angles of incidence on each of the four solar cells are different; in this case $\varphi_4 > \varphi_3 > \varphi_2 > \varphi_1$, therefore, the obtained power on each element will be different (the largest is at the end zone of a wing). If one changes direction of take-off by 180°, the situation will be reverse – $\varphi_4 < \varphi_3 < \varphi_2 < \varphi_1$;

– when executing a roll of an airplane (Fig. 4, *d, f*), the angle of incidence of beams to the surface of solar cells will decrease or increase by the magnitude of the roll while the power of a solar cell will change accordingly.

When integrating a solar power plant and the wing of an aircraft, it is important to arrange cells, or units of cells connected in parallel, sequentially along a wing. In this case, they will have the same orientation relative to the Sun. The phenomenon of varying illumination of constituent elements of a solar panel is unlikely to occur. The existence of a V-wing and structure elements that may shade solar cells degrade the operational parameters of the solar power plant of an aircraft and complicate the estimated model of solar panel operation. Thus, even in the existence of V-likeness with a magnitude of 1°, the power losses of a solar power plant may amount to 2 %. Under the take off/landing modes and during turns, given the instability of operation of solar power plant of an aircraft, it is important to include a battery in the power supply scheme of an aircraft.

To consider the actual operation conditions of solar cells at the surface of a wing and the orientation of an aircraft's wing while performing maneuvers and turns, it is proposed to introduce a functional coefficient $k(\varphi')$. This coefficient considers the difference in the angle of incidence of rays on the solar panel from the angle of incidence on the horizontal plane. In a simplified form, $k(\varphi')=\cos(\varphi')$, where φ' is the difference between the angle of incidence of rays on a solar panel and the angle of incidence on the horizontal plane.

Therefore, electrical power, obtained during the flight, can be described by the following dependence:

$$E_{s.p.} = \eta_{prop.} \eta_{s.c.} \eta_{p.m.p.} \frac{2P_{rad.max.} T_{f.}}{\pi} S_{s.p.} k(\varphi'). \qquad (12)$$

The magnitude, obtained from equation (12), establishes a number of requirements for the efficiency of solar panels and power system of an aircraft. Electric power, obtained during a flight, is the determining factor when calculating the required area of solar panels and the area of a wing.

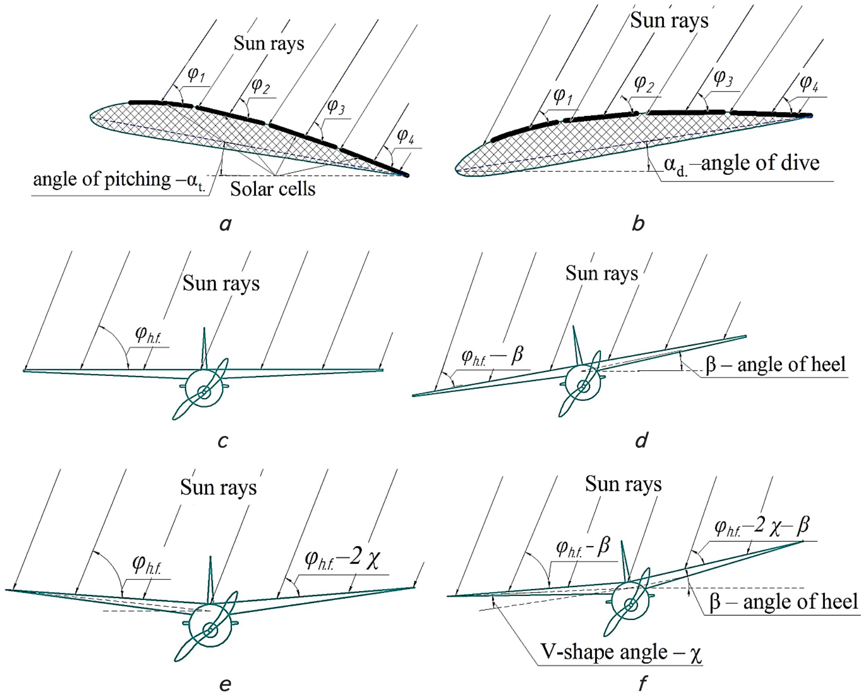

Fig. 4. Features of interaction between sunrays and a wing surface under different flight modes: *a* — take-off; *b* — landing; *c* — horizontal flight; *d* — roll; *e* — horizontal flight, V-shaped wing; *f* — roll, V-shaped wing

The third approach is based on the values of load on a wing. Thus, in studies [16], to determine the weight of the frame of an aircraft, fueled by solar energy, the following dependence was proposed:

$$m_{glider}=\left(\frac{A_1}{\lambda}+A_2\right)S, \qquad (16)$$

where A_1=0.103 kg/m^2, A_2=1.157 kg/m^2 are the design coefficients.

For the optimal prediction of weight of the glider's structure, it is necessary to use a synthesized model, based on the above approaches. That is, based on the existing characteristics of the prototypes and experience, the assessment of the possible weight of each elements of the structure with provision of the design values of loading on a wing was carried out. Loading on a wing is a general parameter for evaluating the weight of the structure and is restricted by technological capacities, flight velocity, and a payload. In a general form, a function for predicting the weight of a glider takes the form:

5. 4. Weight of plane structure

Despite the aircraft size, its shape and purpose, there are elements with constant mass m_{const}. These elements include:

– useful load $m_{u.l}$, which is determined at the initial design stage and depends on the purpose of an aircraft, specific typical tasks and economic constituents;

– control system (autopilot, navigation devices, communications, gauging devices, etc.) $m_{c.s.}$, these components are also selected at the initial stage of creating an aircraft in accordance with the customer's requirements.

Thus, we receive:

$$m_{const}=m_{u.l.}+m_{c.s.}. \qquad (13)$$

The weight of aircraft structure consists of the sum of weights of a large number of interrelated elements, which predetermines the complexity of an analytical model. There are several approaches to the formation of an analytical model of weight of the aircraft structure.

The first approach [14] is to calculate the weight of all elements of the structure (14) (loungeron, ribs, covering, frames, control surfaces, fuselage, empennage, etc.) as functions of the total mass, proportional to the area of a wing. The downside of this approach is that it applies only to aircraft weighing 500–1500 kg:

$$m_{glider.}=\sum_i m_{i.},i=1...k. \qquad (14)$$

The second approach [15] is based on statistical data on gliders. The entire glider of mass $m_{glider.}$ is estimated in the parametric form, dependence includes a wingspan l, a wing area S, the number of tail beams n, and constants A, B:

$$m_{glider.}=A\left(\eta\times S\times l^3\right)^B. \qquad (15)$$

$$m_{glider}=q\sum_{i=1}^{t}f\left(m_i\right),\ i=1...k, \qquad (17)$$

where q is the loading on a wing; k is the number of elements of a glider.

5. 5. Weight of solar panels

When determining the weight of solar panels, it is necessary, first of all, to consider a condition of balancing the total power, generated during the flight, to the total electrical power, consumed at the stage of a horizontal flight. Along with this, it is important to consider the component of solar energy in the provision of power supply at the stages of takeoff, landing and turns. By using dependences (8) and (12), we shall obtain an equation for determining the required area of solar panels:

$$S_{s.p.}=2\pi k'\frac{P_f\times\left(T_{h.f.}+\sum_{i=1}^{m}k\ (\alpha,\beta,\gamma)\frac{T_{in}}{\eta_{char}\eta_{dischar}}\right)}{k(\varphi')\eta_{prop.}\eta_{s.c.}\eta_{p.m.p.}P_{rad.max.}T_{f.}}. \qquad (18)$$

The area of solar cells should be sufficient to accomplish the energy balance of an aircraft:

$$E_r=E_f=k'E_{s.p.}=E_{s.p.}+E_{bat.}, \qquad (19)$$

where $E_{bat.}$ is the power, concentrated in the battery; k'=0...1 is the coefficient considering the degree of participation of solar energy in the aircraft power supply. Thus, at k'=1, the sun energy is solely used for performing the flights.

If, for example, under the modes of takeoff/landing and turns, the battery power is used and the contribution of battery power is one-tenth of the total power, consumed during flight, then we shall receive k'=0.9.

If one has the required area of solar panels $S_{s.p}$ and divides it by the area of one of typical solar element $S_{s.e.}$, we shall receive the number of solar cells, from which the solar panel will be mounted. In addition to the mass of the solar cell $m_{s.e.}$, it is necessary to take into account the weight of protective laminating covering $m_{lam.}$, applied on each element, and the weight of conductors $m_{cond.}$, used for the assembly. As a result, we have

$$m_{s.p.} = \frac{S_{s.p.}}{S_{s.å.}}\left(m_{s.å.} + m_{lam.} + m_{cond.}\right). \quad (20)$$

Based on the fact that the weight of solar panels makes up a significant percentage of the total weight of an aircraft, a rational choice of laminating coating is an important task. The weight of all components of the total mass of solar panels (20) must be minimized.

5. 6. Weight of unit of tracking the maximal power point, weight of battery and of power plant

For the effective operation of solar panels, it is necessary to have an inverter in the system with the function of tracking the maximum power point. There are industrial solutions for monitoring the operation of solar panels, but they are mainly used for stationary application and are not optimized by a weight parameter. Therefore, making the unit of tracking the maximal power point for solar panels is a design task. The mass of this unit may be represented in the form of dependence on the maximal power of solar panels $P_{s.p.max.}$, which in turn depend on radiation, the area and efficiency of solar cells (21):

$$m_{p.m.p.} = \frac{1}{k_{p.m.p.}} P_{s.p.max.} = \frac{1}{k_{p.m.p.}} \eta_{prop.}\eta_{s.c.}\eta_{p.m.p.} P_{rad.max.} S_{s.p.}, \quad (21)$$

where $k_{p.m.p.}$ [W/kg] is the coefficient, which characterizes the weight effectiveness of the unit of tracking the maximal power point.

To predict the weight of industrial components, it is proposed to introduce the following coefficients of weight efficiency: for the engine – $k_{e.}$ [W/kg], for the battery – $k_{bat.}$ [W×h/kg], for the electronic controller – $k_{e.c.e.}$[W/kg]. The values of these coefficients will be defined based on analysis of relevant statistical information (Fig. 5).

In the process of defining the characteristics of weight perfection, the following brands were analysed [17–19]:

– *for engines* – EMAX (Japan), T-MOTOR (China), MultiStar Viking (Japan), NTM (China), Scorpion (China) Hoffman Magnetics (the USA), KEDA (China), TURNIGY Motors (China), Walkera (China) and others (Fig. 5, *a*);

– *for electronic controllers* – Castle (the USA), Dynam (China), Turnigy (China), HobbyKing (China), Favourite (China), ZTWSpider (China), EMAX (Japan), HobbyWing (China), Tower pro (China) and others (Fig. 5, *b*);

– *for batteries* –TATTU (the USA), Giant Power (Australia), Dinogy (the USA), Sanyo (Japan), Gens Ace (the USA), Panasonic (Japan), Turnigy (China), ZIPPY (China), Basher (China), Multistar (China), SAMSUNG (South Korea), KEEPPOWER (China), EEMB (China) and others (Fig. 5, *c*).

The weight of the battery directly depends on the power it can yield to a consumer. Total battery capacity is determined as: $E_{bat.}$[A×h]=I[A]×T[h]. The battery power equals: $W_{bat.}$[W×h]=$E_{bat.}$[A×h]×U[B]. After dividing the power of battery by its weight, it is possible to obtain a generalized weight-energy perfection parameter of the device $k_{bat.}$ (Fig. 5, *c*).

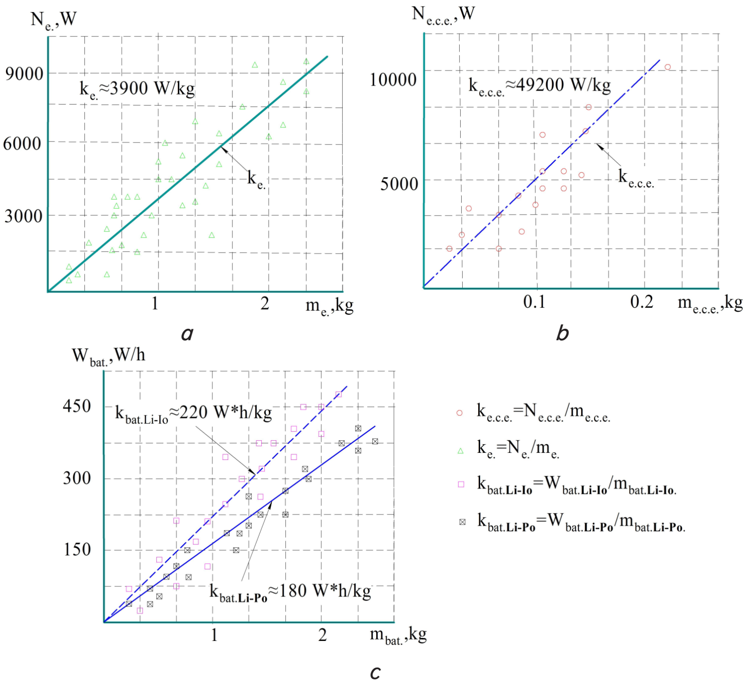

Fig. 5. Mass characteristics of existing industrial components, respectively: *a* – collector-free engines, $N_{e.}$ is the engine power, $m_{e.}$ is the engine weight; *b* –electronic controllers, $N_{e.c.e.}$ – electronic controller, $m_{e.c.e.}$ is the electronic controller weight; *c* – Li-Io and Li-Po batteries, $W_{bat.}$ is the battery capacity, $m_{bat.}$ is the battery weight

It is proposed to determine the actual design weight of the battery for an aircraft, fueled by solar energy, in two ways:

– if we know quantitative contribution of the battery to the operation of an aircraft (deficiency of solar energy is known), then

$$m_{bat.} = \left(1 - k'\right)\frac{1}{k_{bat.}} E_{r.}; \quad (22)$$

– if it is necessary to consider the flight stages, on which the battery will be used in tandem with solar panels, we have

$$m_{bat.} = \frac{1}{k_{bat.}} P_f \times D, \quad (23)$$

where

$$D = \sum_{i=1}^{m}\left[k_i(\alpha,\beta,\gamma) - k_i(\varphi')\right]\frac{T_{i\,i}}{\eta_{char}\eta_{dischar}}.$$

D is the deficit of solar energy under modes other than a horizontal flight.

Magnitude D may be partly compensated for by adding additional area of solar panels, but the battery should remain in the system. Its task is to provide the required engine power under the take-off mode (short-term need for power, exceeding the power of the solar plant by times) and under other uncommon modes.

The power plant should be separated into units: an engine, a propeller, and an electronic controller. Each unit has its own characteristics of efficiency and mass dependences. With the aim of combining the elements of the power plant into a single entity, we shall conduct an analysis of characteristics and determine a generalized parameter of the ratio of power to mass (mass efficiency) for each element.

There are a large number of specialized engines with high mass efficiency, significant variations by power, rotations, weight, reliability, cost, and size. Collector-free engines have the highest mass efficiency; their efficiency is also larger. However, in comparison with collector shield engines, a collector-free engine requires sophisticated control. This engine has three independent windings, the voltage on which must be supplied according to the sinus law and synchronized with the position of the rotor. Weight of the gear box depends on the power, which needs to be transmitted, the coefficient of decrease or increase in rotations and geometric constraints. Weight of the propeller depends on characteristics of an engine (power and engine rotations). Since an aircraft, fueled by solar energy, performs mostly horizontal flights [8], it is necessary when choosing a propeller to consider its efficiency under the cruising mode.

The total weight of the propulsion plant may be described as follows:

$$m_{p.p.} = N\left(\frac{1}{k_{p.}\times\eta_{h.}}+\frac{1}{k_{gearbox}\times\eta_{gearbox.}\times\eta_{p.}}+\frac{1}{k_{e.}\times\eta_{e.}\times\eta_{gearbox}\times\eta_{p.}}+\frac{1}{k_{e.c.e.}\times\eta_{e.}\times\eta_{e.c.e.}\times\eta_{gearbox.}\times\eta_{p.}}\right), \quad (24)$$

where $k_{p.}$, $k_{gearbox.}$, $K_{e.}$, $K_{e.c.e.}$ [W/kg] are the generalized parameters of weight perfection (Fig. 5) (the ratio of power and weight) of the propeller, the gearbox, the electric engine, the electric controller, respectively.

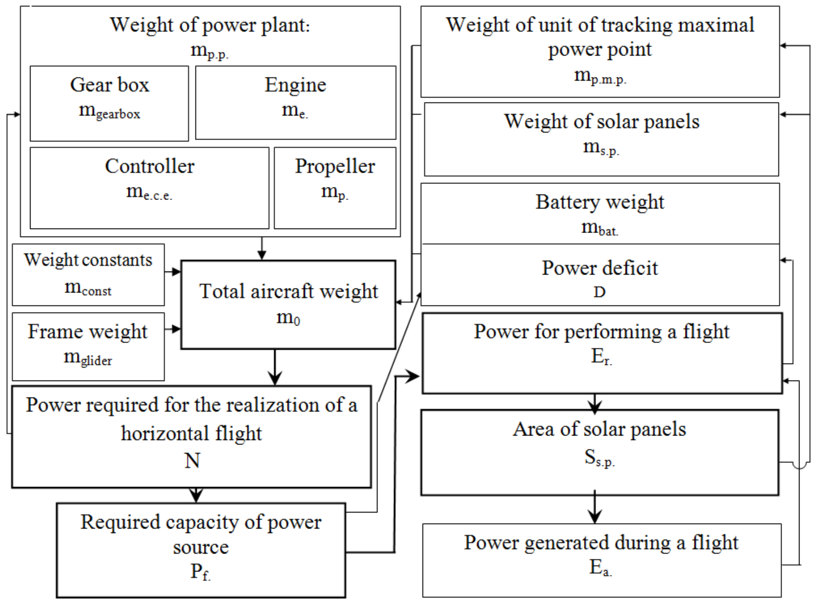

Fig. 6. Generalized mass-energy model of the airplane fueled by solar energy

6. Discussion of results of the synthesis of a generalized mass-energy model

Upon obtaining an analytical model of power consumption for the flight realization, as well as the power generation model and the mass model of an aircraft, we formed a general scheme of mass-energy balance of the airplane fueled by solar energy (Fig. 6). The scheme brings together in a compact form all the dependences, described above, and comprehensively presents features of the synthesis of parameters for aeroplanes fueled by solar energy.

By analyzing the resulting model of an airplane, fueled by solar energy, it is possible to distinguish several groups of parameters (according to classification of A. *North*) [10].

Technological parameters depend on the level of modern technology. These include performance efficiency, mass efficiency of aircraft components (engine, battery, propeller and others).

Operational parameters depend on a typical task that must be performed by an aircraft. These include flight time, payload weight, altitude, and geographical location.

Design parameters are defined during design process. These include area of a wing and a wingspan, area of solar cells.

Since technological parameters can be taken as constants while TT defines operational parameters, then only the design parameters need to be determined unambiguously. A choice of design parameters is the problem of multi-criterial optimization.

Thus, the mass-energy model is the basis for the algorithm of predicting the relevant aircraft parameters. In combination with the algorithm of aerodynamic design [9], we obtain a general sequence for determining the parameters of an aircraft fueled by solar energy.

7. Conclusions

1. The principles of power supply of an aircraft under all flight modes were defined. Under the take-off/landing modes, during turns and under condition of shading and low light, it is expedient to include a battery in the scheme of power supply of an aircraft as the operation of solar panels becomes unstable and power may decrease.

2. The factors that affect the performance efficiency of solar panels are described. For the effective operation of solar panels, it is important to place solar cells or units of solar cells connected in parallel, sequentially along a wing, providing equal conditions of illumination. It is necessary to eliminate the possibility of shading the solar cells by the elements of design under certain conditions of orientation of an aircraft relative to the Sun.

3. The model for determining the weight of an aircraft in general is proposed, which takes into account weight characteristics of industrial components of an aircraft (engine, engine regulator, and a battery). To assess the weight of a glider, it is expedient, based on the existing characteristics of prototypes and the actual practice, to conduct assessment of possible mass of each element of the structure while pro-

viding for the values of generalized characteristics, such as a load on a wing.

4. The calculation model of mass-energy balance of an aircraft, taking into account common operation modes and the laws of generation of solar energy, was received. This model combines technological, operational, design (unknown) parameters and is the basis for the formation of algorithm for choosing the parameters of aircraft fueled by solar energy.

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