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PRELIMINARY STUDY OF AN AIRPLANE FOR ELECTRIC PROPULSION TESTING AT HIGH ALTITUDES

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Abstract

Technology of photovoltaic cells and lithium batteries is being developed rapidly. As a result, attempts to build solar High Altitude Long Endurance (HALE) airplanes are more and more frequent. In the future, such airplanes may appear very useful for the economy because they may replace geostationary satellites in several applications. Unfortunately, data on altitude effect on photovoltaic cells and batteries performance are not easily available. Moreover, acquisition cost of cells is very high. Therefore, a tool for inexpensive testing of cells is needed. This article shows a study of very light unmanned airplane that could be used as a testbed for this purpose. Weight assumptions are presented together with concept of geometry and aerodynamic characteristics. Propulsion system is proposed, so also airplane performance is estimated. Finally, results are discussed leading to the conclusion. It appears that unmanned airplane with maximum take-off weight of 1.3 kg can climb to the altitude of 10 km within 4 hours during sunny summer day about the noon. However, only 30% of such days can be used because of strong winds blowing at high altitudes, quite small optimal airspeed of the airplane and constraints due to Air Traffic Management. Moreover, application of variable pitch propeller is recommended as well as some kind of take-off assist. For example, towing or take-off from the hill is desirable to avoid threats resulting from small climb rate.

Keywords: *Electric propulsion, flight testing, unmanned aerial vehicle*

1. Introduction

Interest in aeronautical electric propulsion systems has been growing for several years. It can be noticed in application of more numerous electric avionic systems instead of hydraulic and pneumatic, in application of electric motors as propulsion of conventional airplanes and in creation of new airplanes types. These new types of airplanes could for example fly for many months at extremely high altitudes. As a result, they could work in the similar way as geostationary satellites [1] thus decreasing demand for them. This would be of particular importance for economy because of reduced service costs as well as for environment due to reduced number of space launchers take-offs. It would be also important from the operational point of view because the number of satellites on geostationary orbit is constrained. However, designers are facing some barriers making the task of very long endurance flights difficult or even impossible to perform. One of the most important is the lack of information on real characteristics of very expensive devices that could be used in propulsion systems. Usually published characteristics were obtained in the laboratory condition at sea level or on the level of laboratory where particular device was created. On the other hand, application in real airplane requires information on real characteristics at different altitudes. Traditionally influence of the altitude was carefully studied in the case of internal combustion engines because of amount of oxygen available in ambient atmosphere on various altitudes for burning the fuel. Most of electric propulsions do not burn any fuels, therefore, they seem to be insensitive to the altitude. In reality, they are exposed to the variation of pressure, temperature, radiation intensity, and spectrum. Each of them may influence the efficiency of the propulsion. A few of these variations can be simulated in the vacuum chamber e.g. variation of ambient pressure and temperature. However, application of good vacuum chamber is usually quite expensive and does not allow for the simulation of radiation intensity and spectrum in full range experienced in the flight. These circumstances suggest that flight-testing on the real airplane would be more useful. A few successful attempts to fly at high altitudes with solar electric propulsion have been already performed (Aerovironment Helios [2], Quinetic Zephyr [3]) as well as attempts to fly with very long endurance (Solar Impulse [4]). Unfortunately, detailed characteristics of their propulsion systems are not widely published. In particular, effect of aging at high altitudes is not revealed in details. Systematic research in this area and publication of results would be precious.

The airplane for such experiments should be inexpensive, so also small a simple in operations. Therefore, it is interesting to investigate how small solar airplane could work for such an application. This article presents a case study of such an airplane.

2. Weight assumptions, structure and geometry

The airplane should be inexpensive, which is usually difficult to achieve. Fortunately, it is not required to fly over night. Moreover, the measurement system could be simple and light since devices as high quality observation systems are not necessary in this application. As a result airplane could be much less complex than usually proposed ones [5-7] and smaller a simpler in operations. Its design could be based on contemporary flying F1A FAI models [8, 9]. In such case, its structure could be as light as 0.4 kg with wingspan as long as 3 m and wing area in order of 0.51 m^2. Wing would have structure consisting of a D shaped torsion box with a spar, ribs, a trailing edge beam, and a polymer elastic skin. The torsion box would be made of one layer of symmetrical carbon fabric with epoxy matrix. It would be very thin so it would be supported densely by ribs made of balsa wood to avoid buckling and to maintain the airfoil shape. Spar would be made of two carbon-epoxy composite rods connected by balsawood. Both the rods and the connector would be wounded around by aramid thread, creating a shear-web. The aft part of the wing would consist of the balsawood ribs covered by strips of carbon-epoxy composite. The trailing edge would be made out of carbon-epoxy composite rod. This kind of wings in F1A models usually has weight of approximately 0.150 kg. These models however usually have smaller span and wing area than assumed here which could suggest that currently considered airplane should have heavier wing. On the other hand, F1A models experience much greater loads during so-called dynamic launch from the tow than the loads assumed for the current design. Therefore, it seems reasonable to assume similar cross-sections of all structural components, which would result with in less than proportional weight increase, to let us say 0.2 kg.

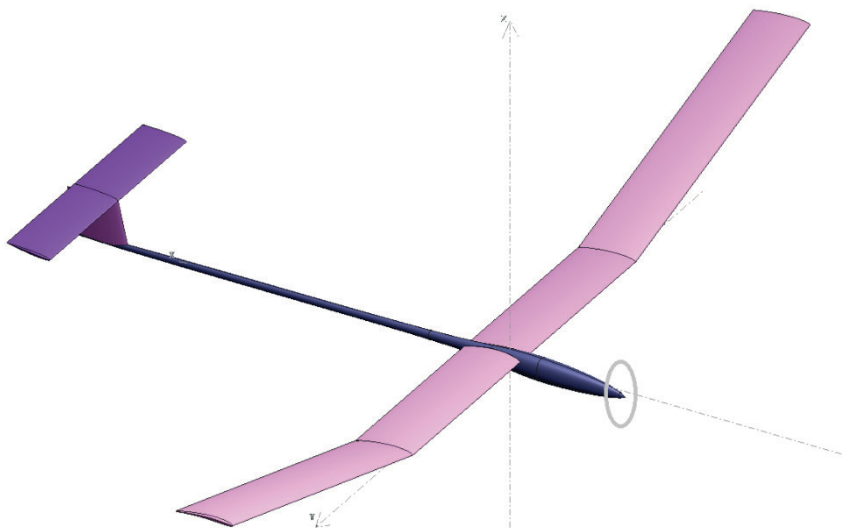

Fig. 1. Conceptual sketch of the airplane

The fuselage would be made of two components: the front part and the tail boom. The tail boom would be made as carbon-epoxy composite tube. The front part would be made of plywood frames and carbon-epoxy composite skin with cutouts for equipment and motor. Altogether, fuselage structure should not be heavier than 0.150 kg. For a comparison F1A, models usually have the weight of the fuselage in order of 0.25 kg, however, with about 0.13 kg of ballast in the nose [10], which is not necessary in the current case.

The empennage would be made of balsawood truss reinforced by strips of carbon-epoxy composite. It should be much lighter than 0.050 kg. These weights are achievable provided that the manufacturer has hands-on experience with this kind of structures.

Airplane should be also equipped with an autopilot and a radio modem to fly at high altitudes. One can assume that both these components together would have the weight not greater than 0.12 kg. Assuming as simplified control strategy as possible (elevator and rudder only) weight of servos controlling the airplane could be as small as 0.020 kg.

Payload would consist of a measurement system with weight no smaller than 0.25 kg. It would be used to investigate the performance of the propulsion system consisting of photovoltaic cells assembly with weight no less than 0.3 kg, an energy conversion system (0.07 kg), a lithium battery (0.05 kg), a supercapacitor (0.01 kg) and a motor with propeller. The motor applied should be of contemporary high performance brushless outruner type to provide sufficient performance. It should be equipped with a variable pitch propeller to adjust for optimal airspeed increase together with growing altitude. Such a propulsion system (e.g. HY25-152C 4D [11]) could have a weight no greater than 0.07 kg. As a result, take-off mass of the airplane could be smaller than 1.3 kg. The concept of such an airplane can be seen in Fig. 1.

3. Energy balance

A maximum of 900 W of beam energy can be collected with an area of 1 m^2 on a summer day at noon [4]. High quality photovoltaic cells have the efficiency of about 22.4% [12]. So 1 m^2 of such cells can provide about 200 W of electric energy. Density of encapsulated cells can be estimated as 0.8 kg/m^2 [4]. Usually it is not possible to cover the whole surface of the wing because leading edge of the airfoil has too small radius of curvature. So let us assume that cells are covering 0.125 m of the chord close to the trailing edge [12]. As a result, we obtain about 0.375 m^2 of solar cells installed. During summer sunny day, they should provide up to 75.6 W to the airplane. After energy conversion, it should be reduced to 70.4 W since energy conversion system efficiency can be estimated as 93% [4]. Assuming that each of 24 cells gives 0.45 V [12], the whole battery would provide the voltage of 10.8 V, which also gives the current of 6.5 A. 2 A would have to be used to run the avionics, so 4.5 A would be available for the propulsion. With motor efficiency as high as 67% [13] we can estimate that 32.7 W would be delivered to the propeller. Then, assuming propeller efficiency in order of 0.5% we would obtain N_A = 16.3 W of power available for flight. Let us assume that this power is constant and does depend on neither airspeed (due to the variable pitch propeller application) nor altitude (ideal case). In the real case, radiation would be growing with altitude, which should increase the power delivered to cells, but falling temperature and pressure together with hard radiation from space may decrease the efficiency of the whole system thus decreasing the power available. Therefore, assumption of constant power seems to be conservative enough.

4. Aerodynamic characteristics

The power available for flight should be now compared with the power required to fly. To estimate this power, airplane from Fig. 1, equipped with the airfoil A-18 [14], was analysed with application of XFLR-5 software [15]. The results of this analysis are visible in Figs. 2-4. Fig. 2 shows the pressure distributions obtained for the angle of attack allowing for maximum climb rate and the elevator deflection providing equilibrium. Fig. 3 shows the angle of the elevator deflection for various airspeeds of the airplane. Finally, Fig. 4 shows the trimmed polar of the airplane. It is accompanied by the polar where drag coefficient was increased by 0.01. The polar calculated with XFLR represents relation between the lift and drag of an ideal aerodynamic body without any extending devices like levers of the control systems, slots between control surfaces or edges of solar cells. Each of these imperfections increases the drag of the airplane. Detailed estimation of this increase is only possible after wind tunnel testing, so at the moment it seems reasonable to assume the second polar for further estimations.

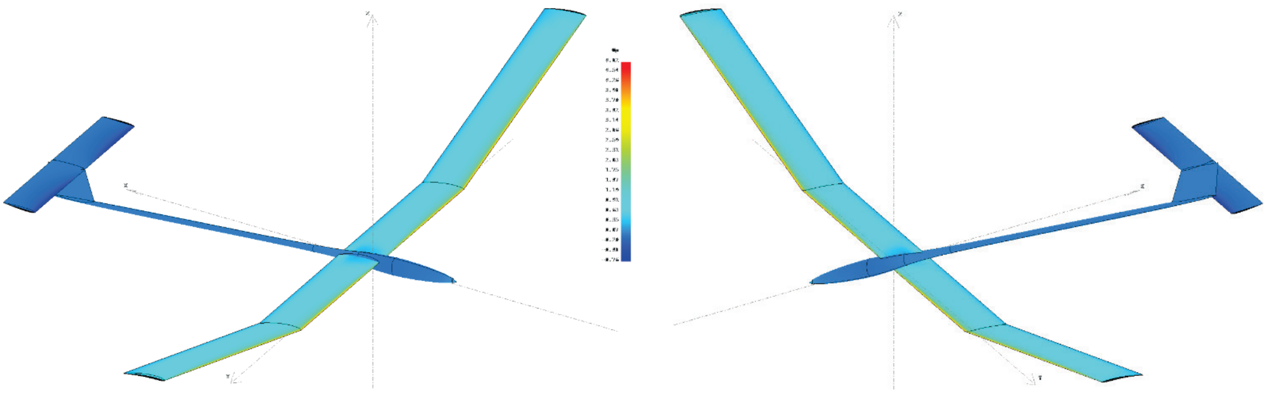

Fig. 2. Pressure distributions obtained for optimal trimmed configuration of the airplane

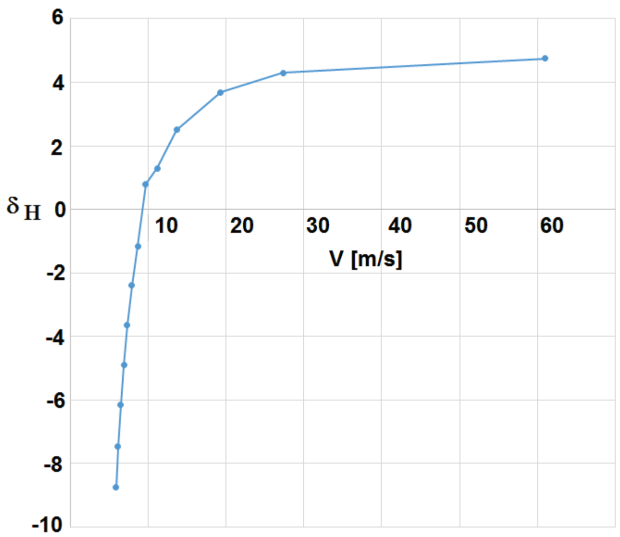

Fig. 3. Elevator deflection necessary to obtain equilibrium in flight with various airspeeds

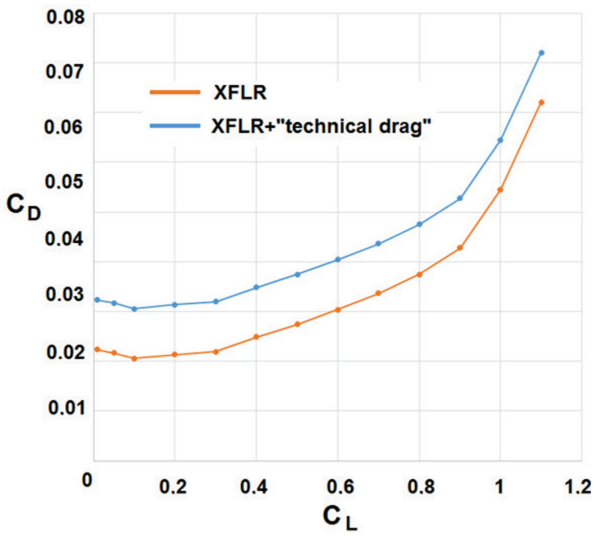

Fig. 4. Trimmed polars: calculated with XFLR and with "technical drag" increase

5. Performance

The power required for flight can be calculated from the equation:

$$N_R = mg\sqrt{\frac{2mg}{\rho SE}}, \tag{1}$$

where:
m – mass,
g – gravitational acceleration, $g = 9.81$ m/s^2,
ρ – air density equal to 1.225 kg/m^3 at sea level and falling with altitude,
S – wing area,

E – power factor, $E = C_L^3/C_D^2$,
C_L – lift coefficient,
C_D – drag coefficient.

Airspeed of the airplane can be calculated according to the following equation:

$$V = \sqrt{\frac{2mg}{\rho S C_L}}, \tag{2}$$

where
V – airspeed.

Finally, rate of climb can be calculated according to the following equation:

$$w = \frac{N_A - N_R}{mg}, \tag{3}$$

where
w – climb rate,
N_A – power available,
N_R – power required.

The result of these calculations for the growing altitude of flight can be seen in Figs. 5 and 6. The first of them shows climb rates in respect of airspeed at various altitudes. The second shows variation of optimal airspeed in respect to the altitude. Moreover, the time necessary to achieve growing altitudes was calculated according to the equation (4). The result can be seen in Fig. 7.

$$t_n = \sum_1^n \frac{2000}{w_{n-1} + w_n}, \tag{4}$$

where:
t – time,
n – altitude in km.

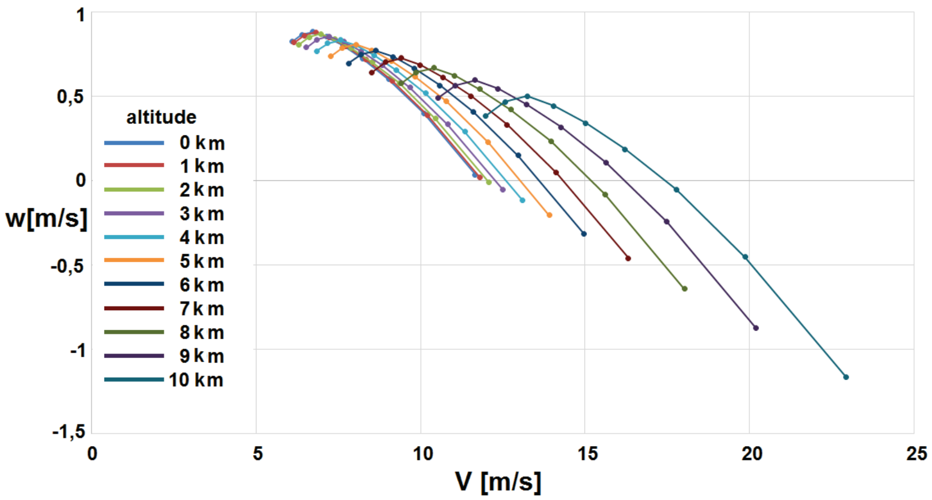

Fig. 5. Climb rate at the altitudes 0-10 km

6. Discussion

As can be seen from Fig. 7, analysed airplane can achieve the altitude of 10000 km within less than 4 hours, which means that it should take-off about 10 a.m. to achieve said altitude about 2 p.m. This is quite good approximation of "noon", so the solar radiation would be utilized in satisfactory efficient way.

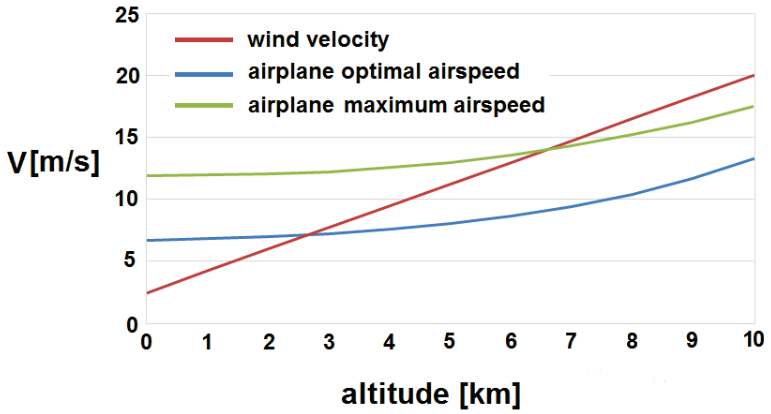

Fig. 6. Airplane airspeeds and average wind velocity in respect to the altitude

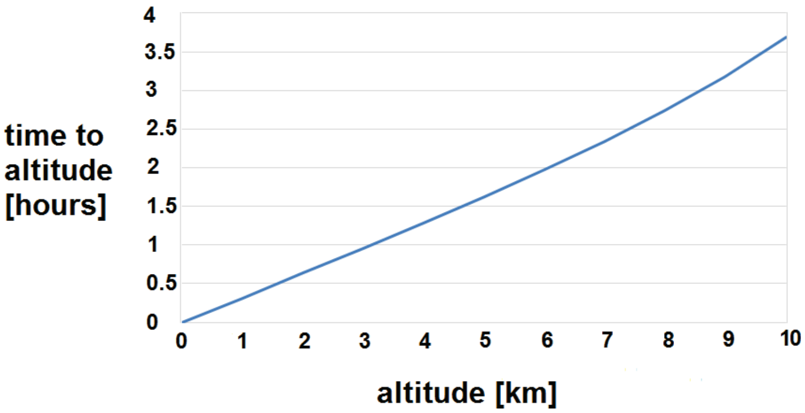

Fig. 7. Time necessary to achieve growing altitudes in ideal conditions

Figure 5 reveals very small climb rate of 0.88 m/s at the sea level, which can be dangerous for the conventional radio controlled take-off from the level of a flat airfield. Therefore, two take-off techniques are considered. The airplane could be towed like F1A FAI models (however, without dynamic launch) or could be hand launched from a hill like F1E [8] FAI models. In both cases, the support from thermal and/or wave atmospheric motions would help to obtain the first several hundred meters of altitude. The take-off about 10 a.m. should facilitate such a climb technique. It should increase the safety and decrease the time of flying at low altitudes, which are the least interesting. Then airplane would continue climbing with its own propulsion alone to the limits set forth by PANSA (Polish Air Navigation Services Agency). During the whole flight the mechanic, electric and thermodynamic parameters of the propulsion system components would be recorded.

Figure 6 shows quite significant variation of the optimal airspeed from 6.73 m/s at the sea level up to 13.25 m/s at the altitude of 10000 m. This is the reason why a variable pitch propeller should be applied. The motor of the airplane should work within defined rpm (rounds per minute) range to maintain the maximum efficiency. It would not be possible in this case with a constant pitch propeller because its pitch would be too large at low altitudes and too small at high altitudes. It would result in rpm decrease due to the motor overloading near the ground and rpm increase at high altitudes due to the motor under loading. In both cases, the motor efficiency would be decreased. Let us assume that a motor with 1400 rpm/V would be used [13]. Therefore, with 10.8 V delivered from the energy conversion system the propeller should rotate with 15120 rpm's which is reasonable for the airplanes of this size. For such a motor, a propeller with diameter of about 0.2 m is recommended. It would become optimal when the blade angle of attack reaches about 5^{o} (the optimal angle of attack of an airfoil). Let us assume that the propeller is designed in such a way that this 5^{o} is achieved when the airplane is motionless with the propulsion running. In this case, the blade angle of attack is equal to the incidence angle, which can be calculated as:

$$\alpha_i = \arctan\frac{p}{\pi D}, \tag{5}$$

where:

α_i – incidence angle at the blade tip,

p – propeller pitch,

D – propeller diameter.

From this equation, the initial pitch can be calculated. In the analysed case, it would be equal to 0.055 m and should be increased immediately after the take-off according to the equation:

$$\alpha = \left(\arctan\frac{p}{\pi D}\right) - \left(\arctan\frac{2V_{opt}}{\omega D}\right), \tag{6}$$

where:

α – angle of attack at the blade tip,

V_{opt} – optimal airspeed of the airplane,

ω – rotational velocity of the airplane.

In the analysed case, for the optimal climb, the pitch should have the value of 0.082 m at the sea level and then 0.108 m at the altitude of 10000 m. This also means the variation of the incidence angle from 5° to 9.78°, which is well within the range of available variable pitch mechanisms since they allow for as high variation as ±45°. However, detailed values should be defined after careful design of the propeller.

The most significant issue resulting from the airplane airspeed may arise from its comparison with the wind velocity at high altitudes. In average, the wind speed should increase from 2.5 m/s at the sea level up to 20 m/s at the altitude of 10000 m [7]. This means that the airplane flying against this wind with the optimal velocity of 13.25 m/s would fly backwards relatively to the ground with speed of 6.75 m/s. This is not acceptable from the air traffic management point of view. The most probable diameter of the space that could be reserved by PANSA for this kind of experiment is no greater than a few kilometres. Therefore, the airplane should circle above the take-off place rather than fly with the wind. From this point of view, the flight with optimal airspeed would be possible to the altitude equal to only 2.9 km. Moreover, the theoretically achievable altitude would be constraint to 6.5 km where the maximum airspeed of the airplane is equal to the average wind velocity. On the other hand, the same source suggests that statistically the wind velocity at the altitude of 10000 m could be smaller than the optimal airspeed of the airplane for approximately 30% of the available time. This means that between June the 1st and August the 31st approximately 27 days would have acceptable wind conditions. Still those should be sunny days.

7. Conclusion

An airplane with maximum take-off weight of 1.3 kg, with wingspan of 3 m and wing area of 0.51 m^2, covered by 0.375 m^2 of photovoltaic cells can take a research payload of 0.25 kg to the altitude of 10000 m within less than 4 hours of a sunny summer day about the noon. However, the climb rate of such an airplane near the ground is smaller than 1 m/s, which is dangerous, thus some kind of take-off assist is recommended, e.g. a tow or take-off from the hill. Moreover, thermal and/or wave atmospheric motions could help to obtain the first several hundred meters of altitude, which are the least interesting from research point of view.

The variation of optimal airspeed from 6.73 m/s at the sea level up to 13.25 m/s at the altitude of 10000 m is significant. Therefore, the variable pitch propeller application is recommended. The optimal airspeed mentioned above is significantly smaller than the average wind velocity at the maximum altitude. Therefore, the experiments with the application of the presented airplane could be performed during 30% of summer sunny days within the year, when the wind velocity at the maximum altitude is expected to be no greater than the optimal airspeed of the airplane.

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