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EVALUATION OF CONCEPTUAL DESIGN BASED ON MANUFACTURED ACTUAL UNMANNED SOLAR PLANE

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Abstract

A long-endurance unmanned solar plane to observe the state of ground as exemplified by nature disaster, animal preservation and exploration was designed and developed.
In order to verify the long-endurance flight as aim of multiple-days, we developed an unmanned solar plane that has 7.6m span main wing and GaAs modules, and modify our conceptual design method based on results of manufacturing and test flight so as to evaluate the mass of airframe and required power with more precision.

1 Introduction

The development of solar plane undertakes the significant role as the symbol of sustainable energy technology, and is proceeding to put to various practical use, example for surveillance on the ground, searching resources and mapping and so on.
In the procedure of conceptual design as first step, there are some estimations which are for solar radiation, aerodynamic force and mass of plane.
The prediction for mass of airframe acts the significant role in conceptual design and has two methods mainly. One is the statistical prediction based on the data of other solar planes which have already been made in past times, the other is practical mass prediction obtained by consideration of the concrete shape of the plane.
In this study, after manufacturing and test flight, by comparing result of conceptual design method and parameters of actual manufactured solar plane, prediction based on unsatisfactory statistics for past solar plane is evaluated.

2 Conceptual Design

2.1 Climate of Jeddah, Saudi Arabia

The daily global radiation on horizontal surface in Jeddah, Saudi Arabia changes monthly through a year as Fig.1[1]. A maximum and averaged daily radiation in Jeddah are 7,271 and 6,002[Wh/m^2] according to these distribution of radiation. And maximum and minimum atmospheric temperature are 39.4 and 18.1 degrees C, respectively. The capability of flight for solar plane depends on the radiation which is varied hourly by air mass because of changing of weather and amount of dust. However, daily global radiation between 6,000 and 7,000[Wh/m^2] were used for conceptual design for simplification in consideration of average and maximum value.

2.2 Solar Radiation Model

Daily and hourly global radiation can be estimated by using the model which is taken into account the relation about the earth-sun geometry and the absorption, scattering and reflection of solar light.

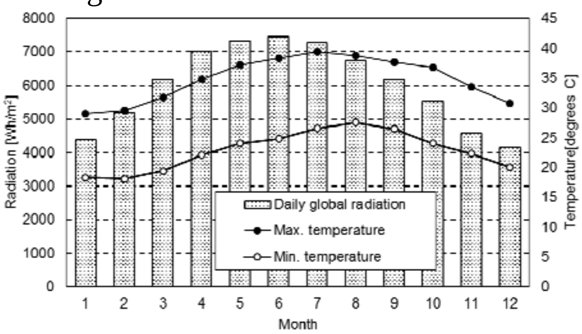

Fig.1 Monthly-averaged daily global horizontal radiation and temperature in Jeddah

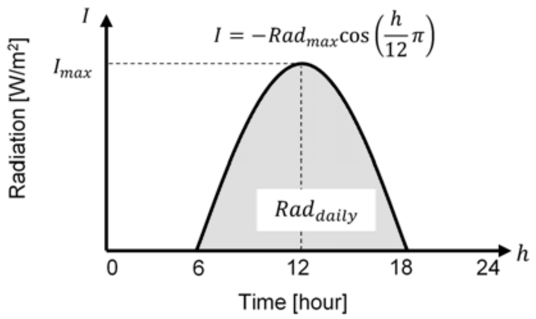

Fig.2 Trigonometric model for solar radiation

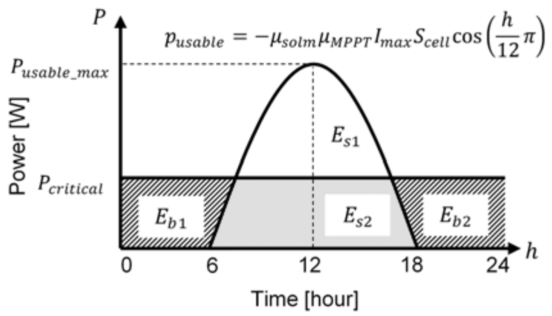

Fig.3 Maximum usable power and critical power

However a trigonometric distribution as shown in Fig.2 is used in this conceptual design for simplification. Rad_{daily} represents an area which is surrounded by trigonometric curve and axis, and equal to the total energy reached to the ground in a day. The radiation becomes maximum at noon in this model, and the maximum radiation P_{max} is obtained by

$$I_{max} = \frac{Rad_{daily}}{(2 \times 12)}\pi \qquad (1)$$

. And the distribution of global radiation p can be estimated as

$$I = \begin{cases} -I_{max}\cos\left(\frac{h}{12}\pi\right) & (6 \le h \le 18) \\ 0 & \left(0 \le h < 6 \text{ and } 18 < h \le 24\right) \end{cases} \qquad (2)$$

Daily global radiation which was mentioned above was used as Rad_{daily}.

2.3 Usable Power and Energy

Generation of power by solar cell and voltage conversion by the maximum power point tracker (MPPT) involved conversion losses. When generation rate of solar module and efficiency of MPPT are μ_{solm} and μ_{MPPT}, respectively, usable power can be represented by

$$p_{usable} = -\mu_{solm}\mu_{MPPT}I_{max}S_{cell}\cos\left(\frac{h}{12}\pi\right) \quad (6 \le h \le 18)$$
$$p_{usable} = 0 \quad \left(0 \le h < 6 \text{ and } 18 < h \le 24\right) \qquad (3)$$

where S_{cell} means an total area of solar cells. Therefore, the usable power gets at its maximum value P_{usable_max} as

$$P_{usable\_max} = \mu_{solm}\mu_{MPPT}I_{max}S_{cell} \qquad (4)$$

at half of a day.

An area surrounded by trigonometric curve and axis in Fig.3 shows the total energy which solar plane can use for driving motor and storing to battery, and is divided to two areas E_{s1} and E_{s2} by a line $P_{critical}$ which is parallel to axis. If required power for level flight equals to $P_{critical}$, since an energy for night flight should be stored from remaining energy of day time, following relation

$$E_{b1} + E_{b2} = E_{s1} \qquad (5)$$

should be secured at least. Therefore, relation between $P_{critical}$ and P_{usable_max} can be derived as below

$$P_{critical} \simeq 0.318 P_{usable\_max}\ , \qquad (6)$$

and actual consumed power for level flight has to be less than $P_{critical}$.

2.4 Consumed Power for Level Flight

Thrust, drag and lift set as T, D and L, respectively, when the plane which its weight is W flies at velocity V on level flight. The required power P_{req} is shown as

$$P_{req} = TV. \qquad (7)$$

However, efficiencies of propeller, motor, reduction gear and electric speed controller

(ESC) should be considered for actual consumed power.

$$P_{consumed} = \frac{P_{req}}{\mu_{prop}\mu_{gear}\mu_{motor}\mu_{ESC}} \quad (8)$$

And efficiencies for charge and discharge of battery, μ_{charge} and $\mu_{discharge}$ are taken into account the consumption of power in addition to these above efficiency when energy is used through the battery.

A power condition which is satisfied for long endurance flight is represented as

$$P_{consumed} \leq P_{cretical} \ . \quad (9)$$

However, for level flight, the velocity L and thrust T must be chosen so as to satisfy conditions that

$$L = W \quad (10)$$

and

$$T = D \quad (11)$$

where

$$L = \frac{1}{2}\rho V^2 S_w C_L \quad (12)$$

and

$$D = \frac{1}{2}\rho V^2 S_w C_D \quad (13)$$

. Lift and drag coefficients, C_L and C_D were estimated by result of calculation for airfoil by FLUENT.

2.5 Mass Prediction

The rate of mass for battery and solar array is higher than the one of other components.

The mass of battery depends on the density of energy for its battery type, and Lithium-Polymer and Lithium-ion battery are used commonly for main battery because of its high energy density and the stable characteristics of discharge. When the density of energy of Lithium-Polymer battery is commonly about 150 [Wh/kg], the mass of battery m_{batt} can be estimated as

$$M_{batt} = \frac{P_{consumed} h_{night}}{R_{se\_batt}} \quad (14)$$

where h_{night} and R_{se_batt} show the term for flight at night time and the density of energy of main battery.

The mass of solar module depends on the materials for encapsulation, and commonly-used materials are Ethylene-Vinyl Acetate (EVA) and Poly Ethylene Terephthalate (PET). The mono-crystalline silicon is used mainly for solar cell, however a solar module which Gallium arsenide (GaAs) is used for solar cell was put on the main wing in this time. An area density of this module is 1.58[kg/m^2]. The mass of solar module m_{solm} can be estimated as

$$M_{solm} = R_{solm} S_{solm}, \quad (15)$$

where R_{solm} and S_{solm} shows the area density and total area of solar module, respectively.

2.6 Result of Conceptual Design Procedure

Efficiencies of propeller, motor, ESC, MPPT were set to values as shown in Table1. Generation rate of solar module μ_{solm} changes as the temperature of solar module varies. It is assumed temperature of solar module is same to atmospheric temperature.

Table1 Efficiencies and Specific values of propulsion device, solar module and battery

μ_{prop}	0.85	[-]
μ_{motor}	0.85	[-]
μ_{ESC}	0.9	[-]
μ_{solm}	0.23 (@300K)	[-]
μ_{MPPT}	0.97	[-]
μ_{charge}	0.97	[-]
$\mu_{discharge}$	0.95	[-]
R_{se_batt}	260	[Wh/kg]
R_{solm}	1.5	[kg/m^2]

Some feasibilities that solar plane can keep flying for long endurance were found as shown in Table 2 and 3 for example. These specifications satisfy the relation of power balance (9) as mentioned above. However in order to obtain wider range of capability about total mass and speed of level flight, daily global radiation should be take more than its average value. Daily global radiation exceeds its yearly-averaged value for 7 months from March to September, and 7,000[Wh/m^2] , 4 months from April to July.

Table2 Example 1 of Result of Conceptual Design Procedure(Rad_{daily}: 6,000[Wh/m^2])

Rad_{daily}	6,000	[Wh/m^2]
b	7.60	[m]
AR	19.0	[-]
S_w	3.04	[m^2]
Airfoil of main wing		E395
V	35.4	[km/h]
$P_{critical}$	77.8	[W]
P_{cruise}	77.7	[W]
Mass Prediction		
M_{batt}	4.9	[kg]
M_{solm}	2.5	[kg]
M_{af}	5.6	[kg]
M_{total}	13.0	[kg]

Table3 Example 2 of Result of Conceptual Design Procedure(Rad_{daily}: 7,000[Wh/m^2])

Rad_{daily}	7,000	[Wh/m^2]
b	7.60	[m]
AR	19.0	[-]
S_w	3.04	[m^2]
Airfoil of Main Wing		E395
V	32.8(min)	[km/h]
	37.5(max)	[km/h]
$P_{critical}$	90.8	[W]
P_{cruise}	64.5(min)	[W]
	89.8(max)	[W]
Mass Prediction		
M_{batt}	5.6	[kg]
M_{solm}	2.5	[kg]
M_{af}	5.6	[kg]
M_{total}	13.8(min)	[kg]
	15.9(max)	[kg]

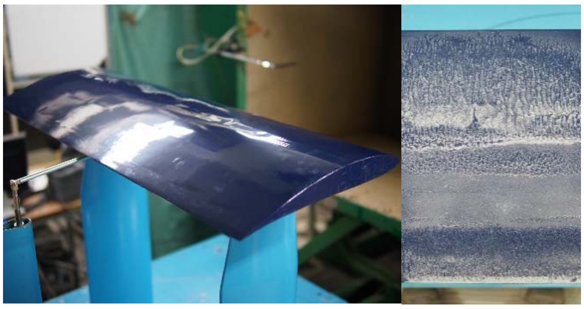

Fig.4 Wind tunnel test and result of oil-flow

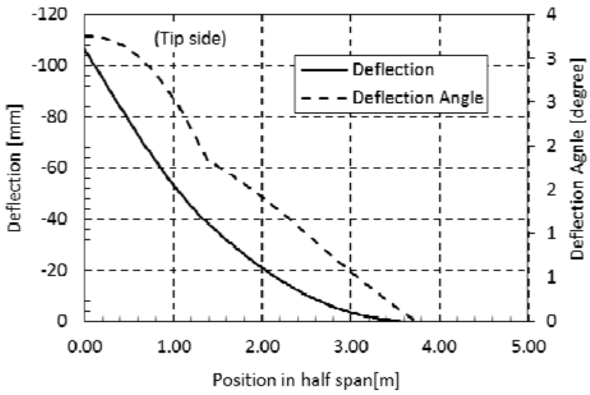

Fig.5 Predicted deflection of main wing

The specification of solar plane for long endurance was obtained. And, in case that the total mass of manufactured plane exceeds the estimated total mass, the total mass should be remained less than 15.9[kg] to remain the feasibility for long endurance from the view point of mass.

3 Manufacturing

In this design, both methods were performed. In particular, after selecting the airfoil E395 for main wing by wind tunnel test as shown in Fig.4, the material, structure of spars and shape of cross-section of each part of which main wing is composed were determined in consideration of the predicted deflection of main wing owing to the aerodynamic load and structural weight as shown in Fig.5.

The airframe of plane was manufactured by using wood mainly as material because of manufacturing skills and easiness of processing.

And thrust type of propeller is pusher and the inverted V-tail was chosen because of increasing thrust efficiency in consideration for interference with wake of propeller. Area of tail was determined by tail volume. Features of our solar plane are as blow.

- 7.6m span, 19 aspect ratio main wing
- Box structure of main wing
- GaAs solar module
- Pusher type propeller as thrust method
- Inverted V-tail
- Twin-boom airplane

And shape of a solar plane which manufactured is as shown in Fig.6.

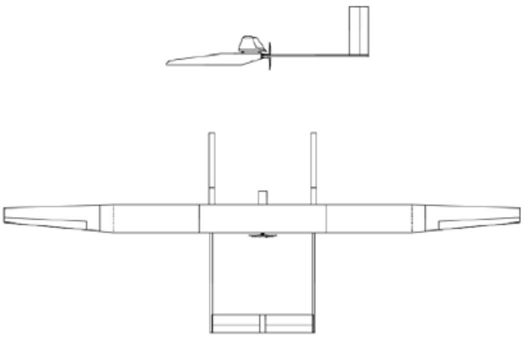

Fig.6 Side and top view of solar plane "SunFalcon2"

Fig.7 SunFalcon2 in level flight

Fig.8 Sight from onboard-cam

4 Test flight and estimation of flight data

Test flight was performed several times at Ojima RC Skyport in Japan as shown in Fig.7 and 8. And flight data was recorded by data logging system which was on board. Air speed, GPS data, altitude, heading and attitude of each flight were obtained. In addition to these data, voltage and current sensor which are connected between solar module and MPPT kept recording the generation of solar power on each panel during flight, simultaneously.

A part of flight data during straight and level flight is shown in Fig.9. Our solar plane flies on rectangle course, which total length is about 2 km, at 100m altitude. It is clear that when flying at an average speed 9.7[m/s] which is near the design speed, our solar plane consumes 94.3[W] power. At the same time, the power which solar modules on the main wing generates reaches 230[W] averagely.

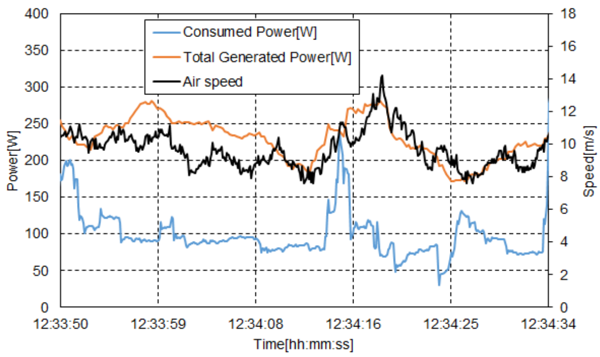

Fig.9 flight data during level flight

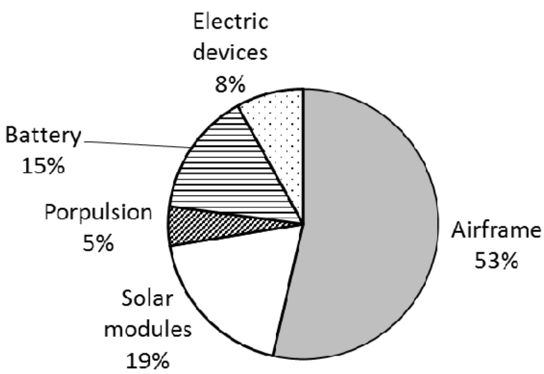

Fig.10 Distribution of mass of components of SunFalcon2

5 Conclusion

Flight of manufactured solar plane “SunFalcon2” was performed successfully and flight data can be obtained. Actual consumed power for level flight around design speed exceed slightly to prediction value of concept design. In order to predict the power, drag and lift force based on coefficients of lift and drag of airfoil which was calculated by FLUENT were used in this conceptual design. It is necessary that the procedure of estimation of drag force for fuselage which its shape is still not determined exactly.

As shown in Fig.10, the rate of airframe mass occupies more than 50% of total. This characteristics is also wooden solar-plane, however sufficient amount of required battery couldn’t be mounted.

And total mass of manufactured SunFalcon2 reaches 14.5[kg] finally. Especially, the mass of airframe becomes heavier than prediction of arranged Noth’s formula[2]. The prediction formula is needed to improve more accurately so as to be suitable for materials and size of solar plane.

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