HALE UAV ITB perpetual flight

Mochammad Agoes Moelyadi¹), Muhammad Fikri Zulkarnain²
Flight Physics Research Group
Faculty of Mechanical and Aerospace Engineering
Institut Teknologi Bandung
Jl. Ganesha 10 Bandung 40132
Indonesia

¹moelyadi@ae.itb.ac.id
²zulkarnain.fikri@gmail.com

Abstract. The challenge developing High Altitude Long Endurance (HALE) UAV is to obtain the ability endurance of more than 24 hours (perpetual flight). The ability to fly for a long time needs to consider: high aerodynamic efficiency, high motor-prop efficiency, hybrid battery-solar panel energy source, light weight structures, efficient control, and optimum flight mission. This paper discusses about strategy, method and requirements to calculate perpetual flight mission for the case of HALE UAV ITB.

1. Introduction

Development of a High Altitude and Long Endurance (HALE) UAV may align to current issues such as regional border, disaster, and foreign areas. Various HALE has been developed as seen Figure 2. One of them is Zephyr UAV [1-3]. The development of Zephyr UAV starts at 2003 with only 15 minutes’ endurance and climb to 27,000 feet, to set a record with Zephyr-s at 2018 flying for 26 days with recorded highest altitude at 74,000 feet.

Atlantik Solar is a small HALE platform, which record 3 days endurance flying at constant altitude of 2,000 feet [4]. Solar Impulse in an example of high altitude long endurance manned aircraft, which has a record of 5 days of flight with the highest altitude of 28,000 feet [5]. Korean Aerospace Research Institute has developed a series of HALE UAV [6], with the latest design EAV-3 which has reached 18,000 km by using own design propeller at 2018 [7]. ApusDuo is a HALE UAV developed by UAVOS, which has multi-boom, tandem wing configuration [8-10].

The development of High-Altitude Long Endurance UAV in ITB is a part of the ITB UAV Development, as shown in Figure 1, with a mission to develop a UAV platform that can use for surveillance and controlled the territory of the Republic of Indonesia. HALE ITB has started to be developed since 2016, and this development includes design, prototyping and structural and flight testing. The performance of HALE UAV ITB previous iteration with MTOW of 20 kg and a wing span of 12 meters has been calculated by Hakim [11]. It has a mission to fly to 20,000 feet for only 20 hours. The current iteration of HALE UAV ITB (Version 4) is designed to have higher aerodynamic characteristics, higher operational capabilities, while also has better structure efficiency compared to previous versions. The newest iteration of HALE UAV ITB has 50 kg MTOW with a mission to fly at more than 50,000 feet and fly for more than 24 hours.
The challenge of developing HALE UAV is to design an aircraft which can reach a very high altitude and obtain long endurance by flying at that altitude. Fulfillment of those two requirements may need to consider several aspects: optimum aerodynamics, optimum motor and propeller combination, optimum battery and solar panel, optimizing flight control and automation, minimize weight, and optimize mission profile. In the case of HALE UAV ITB, minimum energy concept is used, of which total energy required during flight must be minimized.

Very high aerodynamic efficiency is usually achieved by using a very high aspect ratio wing, which resulted in a very minimum induced drag. Motor and propeller design is very important for both climb phase and cruising phase. Usually, this is achieved by developing a propeller specially designed for high altitude flight, as used by Zephyr [12] and EAV-3 [7].

To achieve long endurance, HALE UAV used battery as energy storage for night flight, and solar panel to charge the battery during the day. If possible, the battery with high energy density and solar panel with high efficiency should be used.

Airframe weight needs to be as low as possible, to increase battery weight and reduce total weight. Usually there are two strategies, by using relatively low load factor design as used by Zephyr and EAV-3, or by using flexible wing as used by UAVOS [13].

Final aspect to be considered is the mission profile. The most basic one is climb and then cruise at a constant altitude, which is used by Atlantik Solar [4]. However, as observed from the larger HALE UAV, as shown in Figure 3., there are problems with using this mission profile, especially due the weight of battery [10]. Thus, to reduce the weight of battery, at night, the aircraft will descend into lower altitude, as used by Zephyr [3], Solar Impulse [5], and UAVOS [10]. After the night flight, the aircraft will climb back into its intended altitude to continue cruising during the day.
Figure 3. Mission Profile of several HALE UAV

To make sure HALE ITB V4 can fulfill its mission, a new analysis must be conducted to obtain feasibility analysis for HALE UAV ITB performance. There are three mission profile to be analyzed: 20-hour flight at 20,000 feet; more than 24-hour flight at 20,000 feet; and more than 24-hour flight at altitude of at least 50,000 feet.

2. Theory and Methodology

The performance calculated will be the optimum climb and cruise condition, battery weight, and solar panel area, which fulfill those mission. Method of energetic simulation, which simulate energy obtained and energy used during flight, is used to validate the calculation. The methodology is shown in Figure 4. Several variables such as aerodynamic efficiency, propeller efficiency, airframe weight, battery density, solar panel efficiency, etc., will be varied, to obtain the requirement for each mission profile. Spreadsheet is used to calculate aircraft performance and calculate energetic simulation.

2.1 Aircraft Performance Calculation

Aircraft is assumed to four phases of flight: climb, day cruise, glide, and night cruise. Climb, cruise, and glide performance use equations from Reference [14]. Motor and propeller performance will use NACA propeller design from reference [15] to match motor and propeller from T-motor [16]. This is done as T-motor specifications are only provided for sea level static condition, while aircraft performance calculation needs to consider speed and density. It is found that combination of motor and propeller is close to a 14 degrees’ pitch NACA propeller. The main output of aircraft performance calculation is to obtain throttle and power required during each flight phase, which will be used in battery, solar panel, and energetic simulation calculations.

There are four different motors considered: MN1005, U12, U13, and U13II. Two diameter of propeller are considered, 30 inches and 32 inches. It is assumed that the lowest throttle settings possible is 40% for MN1005 and 50% for others, as the data provided in motor specifications. The motor specifications used are maximum power, maximum thrust, and maximum rpm, while their variation at various throttle is assumed to be similar which is shown in Figure 5.
2.2 Battery and Solar Panel Sizing

Solar cell needs to be able to provide energy for the entire flight, while the battery is used during night. From aircraft performance calculations, energy required can be calculated. Total energy required divided by total energy produced by solar cell will yield solar cell area. Total energy required during night and two hours during day will be used to obtain the battery size. The battery size and solar panel area is then iterated during energetic simulation to obtain the most optimum design.

2.3 Energetic Simulation

Energetic simulation is used as a method of validation for solar panel and battery sizing, as well as aircraft performance and weight sizing, as has been done in reference [4]. As shown in equation 1, this method calculates the rate of battery energy change as a power expended and gained throughout the flight. By using discretization, battery energy state as a function of time can be obtained by multiplying power expended and gained throughout the flight with \( \Delta t \), as shown in equation 1. As the calculated method is not very detailed, the value of \( \Delta t \) may not need to be small and the value of half an hour is deemed to be accurate enough for the calculation.

\[
\frac{dE_{\text{battery}}}{dt} = P_{\text{solar}} - P_{\text{out}}
\]

\[
E_{\text{battery}}(t) = (P_{\text{solar}}(t) - P_{\text{out}}(t))\Delta t
\]

Power expended \( P_{\text{out}} \) was calculated previously during performance calculation and is varied according to the aircraft flight phase and the mission profile. An additional constant power of 10 W is added to simulate other system such as flight control and actuator. Charging power of the solar cell \( P_{\text{solar}} \) is obtained by multiplying solar cell area with irradiance. The irradiance model, as a function of time, used a modified version from reference [17] [18]. The irradiance model is assumed to be 12 hours and start at 6 in the morning to better fit condition in Indonesia. Maximum irradiation is assumed to be the efficiency of solar cell.

3. Results and Discussions

To obtain the minimum energy, calculating the energy and power required for every altitude is done. Climb time, total climb energy, and cruise power for altitude 20,000 and 50,000 ft is shown in Figure 6. At an altitude of 20,000 feet, the most efficient for climbing is MN1005x4 engine. However, four MN1005x4 engines have higher required cruise power compared to three engine MN1005. This, as well as for U13, and U13II is due to low altitude and assumed lower limit of engine throttle, the aircraft cruise at angle of attack lower than the optimum angle of attack. The next optimum engine configuration is MN1005x3 which has lower required climb and cruise energy. This is due to higher number of motor needs lower throttle for each motor, while for electric motor observed, the motor has higher efficiency at lower throttle.
For altitude of 50,000 feet, only three combination of engine is capable to climb to this altitude, which are MN1005x4, U13x3, and U13IIx2. For climbing, the best configuration is U13IIx2, which has the lowest energy required and climb time. Lower climb time is very important because HALE UAV needs to be able to escape from lower altitude quickly to avoid more turbulent air. However, for cruise performance, the best option is using MN1005x4. However, it should be noted that has worse climb performance, and four engines may lead to complexity in system design compared to only two engines.

Variation of MTOW, aerodynamic efficiency, and propeller efficiency and its effects on energy consumption is also studied. As seen in Figure 7, the increase in MTOW resulting in the increase of energy required both during cruise and during climb.

Variation of aerodynamic efficiency and propeller efficiency is shown in Figure 8. The aerodynamic efficiency is represented by maximum L/D, while the propeller efficiency is represented by NACA equivalent propeller pitch. The better the efficiency, power required and energy required can be reduced. The aerodynamic efficiency has greater effects for cruise performance, while propeller efficiency is having greater effects for climb performance. One of the findings during calculation is that the typical propeller efficiency encountered is only 0.2 to 0.4 during climb and 0.6-0.7 during cruise, which is relatively low.

**Figure 6.** Effect of Variation on engine combination on performance.

**Figure 7.** Effect of variation on MTOW, 2xMN1005, L/D 27, 10deg prop.
3.1 Perpetual Flight

The main result for energetic simulation are motor-propeller configuration, aerodynamics efficiency, airframe weight requirements, battery requirements, and solar panel requirements, which fulfill the three mission case previously discussed. These results are shown in Table 1. As shown in Table 1, the MTOW is also increased due to increase reserve weight for airframe.

The mission profile in Figure 9 can be divided into two parts. The first part is for the first 24 hour of the flight, which includes takeoff and climb from sea level to desired altitude, day cruise at desired altitude, descending from desired altitude to lower altitude.

|                          | Case 1      | Case 2      | Case 3      |
|--------------------------|-------------|-------------|-------------|
| Max altitude             | 20,000 feet | 20,000 feet | 50,000 feet |
| Night altitude           | 5,000 feet  | 5,000 feet  | 25,000 feet |
| Endurance                | 21 hour     | more than 24 hour | more than 24 hour |
| MTOW                     | 50 kg       | 60 kg       | 70 kg       |
| Wing Loading             | 2.1 kg/m$^2$| 2.1 kg/m$^2$| 2.1 kg/m$^2$|
| Power Loading            | 2.2 kg/hp   | 2.2 kg/hp   | 1.4 kg/hp   |
| Propeller                | 30x10.5” (off the shelf) | 32”, higher efficiency | 32”, higher efficiency |
| Max L/D                  | 22          | 27          | 33          |
| Airframe Weight          | 60%         | 50%         | 30%         |
| Battery Weight           | 10.3 kg     | 18 kg       | 29 kg       |
| Battery Energy Density   | 265 Wh/kg   | 265 Wh/kg   | 350 Wh/kg   |
| Solar Cell Weight        | 7.7 kg      | 8.4 kg      | 16.2 kg     |
| Solar Cell Area          | 11 m$^2$    | 14 m$^2$    | 27 m$^2$    |
| Solar Cell Efficiency    | 14%         | 21%         | 27%         |
| Solar Cell Area Density  | 0.7 kg/m$^2$| 0.6 kg/m$^2$| 0.6 kg/m$^2$|
The mission profile for Case 1, shown in Figure 9, is a climb to and cruise at 20,000 feet for 9 hours, and then glide to 5,000 feet and cruise for 6 hours. The climb started later at 7 o’clock to take advantage of larger energy absorption from solar power, which also decreased battery weight. The results of energetic simulation are shown in Figure 10.

The mission profile for Case 2 is similar to Case 1, at which at day the aircraft cruise at 20,000 feet while at night the aircraft descend to 5,000 feet. For Case 2, the aircraft can climb earlier than Case 1 at 6 o’clock or earlier, as the battery requirement, as seen in Case 2 energetic simulation results in Figure 11, is defined by the low altitude night cruise. The following day, the aircraft start to climb from 5,000 feet to 20,000 feet at 9 o’clock.

For Case 3, the climb starts at 6.30 AM for day 1 and 9.00 AM for the following day, to lower the battery requirement. The aircraft cruise at 50,000 feet during day and descend to 25,000 feet at night. Due to the larger difference in day-night cruise and higher altitude, the total time of high altitude cruise is only lower compared to Case 2. The energetic simulation for Case 3 is shown in Figure 12.

4. Conclusion

Study has been conducted for three cases: Case 1 – altitude 20,000 feet and 21-hour endurance; Case 2 – altitude 20,000 feet and endurance at least 24 hours; and Case 3 – altitude of at least 50,000 feet and endurance at least 24 hours. The performance has been calculated based on power and energy requirements for flight for each case. A design requirement including MTOW, aerodynamic, motor-propeller combination, airframe weight, battery requirement, and solar panel requirements has been developed. Case 1 to 3 has more stringent requirements due to the requirement for higher endurance and higher altitude. The mission profiles to fulfill mission Case 1, 2 and 3 have also been developed, parallel to the design requirements. For battery saving, the aircraft fly at lower altitude at night compared to day cruise. Case 1 and 2, night altitude is at 5,000 feet while Case 3’s night altitude is 25,000 feet.
For future works, a more detailed calculation needs to be done, which may include maneuver, environment, and electrical efficiency. The more detailed calculation may need a more sophisticated program or code to run, such as using python. A study on the aircraft variable included in the calculation may need to be conducted. This includes: aerodynamic characteristics; propulsion technology; construction and structure; battery, solar panel, and energy management; and also operational and control aspect. Test and experiment may need to be made to further deepen the knowledge for those aspects.

References
[1] Jane’s 2017 High-flying bird: Zephyr remains in the vanguard of solar-powered flight
[2] Rapinett A 2009 Zephyr: A High Altitude Long Endurance Unmanned Air Vehicle (Surrey: University of Surrey Dissertation)
[3] Thisdell D 2018 Airbus sets flight endurance record with Zephyr UAV. [Online] August 8, 2018. [Cited: August 26, 2020.] https://www.flightglobal.com/airbus-sets-flight-endurance-record-with-zephyr-uav/129186.article.
[4] Oettershagen P et al 2015 A solar-powered hand-launchable UAV for low-altitude multi-day continuous flight. IEEE International Conference on Robotics and Automation
[5] Solar Impulse Foundation Our Adventure. [Online] https://aroundtheworld.solarimpulse.com/adventure.
[6] Hwang S J, Kim S G and Lee Y G 2016 Developing High Altitude Long Endurance (HALE) Solar-powered Unmanned Aerial Vehicle (AUV) Journal of Aerospace System Engineering 10 pp 59-65
[7] Park D, et al 2018 Design and Performance Evaluation of Propeller for Solar-Powered High-Altitude Long-Endurance Unmanned Aerial Vehicle International Journal of Aerospace Engineering 2018
[8] UAVOS UAVOS ApusDuo AIRCRAFT COMPLETED FLIGHT TESTS. [Online] https://www.uavos.com/about-us/press-releases?id=120.
[9] UAVOS New UAVOS HAPS ApusDuo Variant Successfully Completed Test Flight. [Online] https://www.uavos.com/new-uavos-haps-apusduo-variant-successfully-completed-test-flight.
[10] UAVOS THE EXPERIENCE OF UAVOS IN THE CREATION OF HAPS. [Online] https://www.uavos.com/the-experience-of-uavos-in-the-creation-of-haps.
[11] Hakim M L, et al 2018 Solar Cell to Support Perpetual Flight of High Altitude Long Endurance UAV ITB Journal of Physics: Conf. Series 1005 012038.
[12] de Mattos B S, Secco N R, and Salles, E F 2013 Optimal Design of a High-Altitude Solar Powered Unmanned Airplane J. Aerosp. Technol. Manag., São José dos Campos 5 pp 349-361
[13] Стратилатов А, et al 2020 Method for controlling an aircraft and aircraft (variants) WO2020056481A1 Worldwide
[14] Raymer D P 1992 Aircraft Design: A Conceptual Approach (Washington D.C. : AIAA)
[15] McCormick B W 1979 The analysis of propellers including interaction effects (NASA)
[16] T-Motor T-Motor Store https://store-en.tmotor.com/
[17] Duffie J A 2013 Solar Engineering of Thermal Processes (John Wiley & Sons)
[18] Noth A 2008 Design of Solar Powered Airplanes for Continuous Flight (Zurich : ETH Zurich)