Aerodynamics, Stability and Control Analysis of Tactical Solar Power UAV

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Abstract
This paper addresses the fundamental aerodynamics, stability, and control analysis of a solar power Unmanned Aerial Vehicle (UAV) as a part of the preliminary design stage. The tactical solar-powered UAV addressed in this paper is primarily developed for intelligence, surveillance, and reconnaissance (ISR) missions at low altitude. Moreover, such design also has a dual-use capability, which could be utilized in both military and civilian domains. The aerodynamic characteristics of the UAV are obtained from both computational fluid dynamics analysis technique and the wind-tunnel testing at the design operating Reynolds number ranging from $1 \times 10^5$ – $4.5 \times 10^5$. The fundamental aerodynamics coefficient consists of lift, drag, and pitching moment variations versus the angle of attack. The stability and control analysis was carried out based on the small disturbance theory in correlation with the XFLR5 software. The results show that the tactical solar power UAV design could achieve high aerodynamic efficiency at a 4-degree angle of attack which is corresponding to the lift-to-drag ratio of 20.05. Also, the analysis results confirm that the design possesses positive static and dynamic stability at the design cruise flight condition.

Keywords: Aerodynamics, Stability and Control, Solar Power UAV

1. Introduction
Due to the ability of harvesting additional energy from the solar ray, the unmanned aircraft equipped with solar-powered technology could achieve flight endurance further than that of the conventional platform which is solely relying on the battery cells. Hence the popularity of the solar-powered UAV research has increased over the years [1-5]. Based on the current technology the solar-powered UAV could be developed to deliver high flight endurance from 5 hours up to the complete perpetual flight, provided that the degradation of the subsystem components is neglected. Moreover, the solar-powered UAV could be employed for both military and civilian applications (dual-use). The Royal Thai Air Force (RTAF)’s solar power UAV concept presented in this paper is designed primarily for the military's Intelligence, Surveillance, and reconnaissance (ISR) operation at low altitude with enhancing flight endurance [6]. This paper will discuss the key aerodynamic characteristics of the aforementioned design concept as well as the stability and control analysis conducted as part of the preliminary design phase.

The first part of this paper will discuss the design overview of the solar-powered UAV concept followed by the discussion on the design's aerodynamic characteristics obtained from both computational fluid dynamics analyses and wind-tunnel testing.
computational and experimental approaches. Next, the stability and control analysis will be discussed. Finally, the conclusions from the analysis will be addressed along with suggestions for future work.

1.1. The tactical solar power UAV Design Concept

Following the discussion during the design review process, it is decided that the empennage design configuration is to be changed from a T-tail into a V-tail arrangement for the lower part counts. The wing planform geometry is also changed from pure rectangular into the prismatic shape with a constant chord at the inboard section for better aerodynamic characteristics while providing a structural and manufacturing advantage. The revised concept design illustrated in figure 1 has a total wing area of 1.231 m², in which 69% of the total planform area is occupied by the solar cells array. The revised V-tail design layout is conducted to satisfy the required ‘projected’ horizontal and vertical planform area. The overall dimension and mass properties of the revised design concept are illustrated in table 1.

![Figure 1. The tactical Solar Power UAV’s layout](image)

| Wing | Tail | MTOW | 3.88 kg |
|------|------|------|---------|
| airfoil | SG6043 | airfoil | NACA0012 | Ixx | 0.6449 kg.m² |
| wingspan | 3.37 m | Type | V-tail | Iyy | 0.3422 kg.m² |
| aspect ratio | 13 | V-area | 0.124 m² | Izz | 0.9807 kg.m² |
| wing area | 1.23 m² | H-area | 0.0715 m² | Ixz | - |
| incidence angle | 2 deg | | | CG | @37.88% MAC |

Once the configuration of the design concept is defined and frozen, the preliminary design phase could now be executed. In this paper, the aerodynamic and stability and control analysis is the main discussion.
2. Aerodynamics Characteristics

The aerodynamic characteristics of the design concept are observed using both computational and experimental approaches. Two computational aerodynamic tools including the Vortex Lattice Method (VLM) and the commercial Computational Fluid Dynamics (CFD) software are implemented. Also, an aerodynamic experiment using a sub-scale model in a subsonic wind tunnel is performed. Both computational and experimental studies are conducted at the Reynolds number ranging from $Re \ 1 \times 10^5$ - $4.5 \times 10^5$ based on the design operating speed. The lift, drag, and pitching moment coefficient ($C_L$, $C_D$, and $C_m$) of the air vehicle are observed at various angle-of-attack. The stability and control analysis are conducted based on the small disturbance assumption implemented in the XFLR5 software tool.

2.1 Aerodynamics calculation by XFLR5 and CFD

The XFLR5 is an open-source design tool that could be implemented for an initial aerodynamic study as well as stability and control analysis in the early stage of the aircraft design studies [7-9]. The solar-powered UAV model implemented in the XFLR5 consists of wings and V-tail components, which will be used for further stability and control analysis. The 3-D wing and plane analysis are performed in XFLR5 based on the Vortex Lattice Method (VLM).

As the aerodynamic result obtained in XFLR5 are reasonable only in the linear region. The CFD analysis is implemented to observe the aerodynamic characteristics of the non-linear region such as stall. In this study, the CFD simulations are performed using the Spalart-Allmaras turbulence model through the ANSYS FLUENT V16. Figure 2 illustrates the air vehicle model implemented in the XFLR5 and CFD environment.

![Figure 2. The tactical Solar Power UAV Model in (a) XFLR5, (b) CFD](image)

2.2 Aerodynamics by wind-tunnel Testing

The aerodynamic experiment of the air vehicle is performed in the Subsonic Research Wind Tunnel (SRWT) facility (figure 3(b)) located at the Aeronautical Engineering and Aviation Division at the Navaminda Kasatriyadhiraj Royal Air Force Academy (NKRAFA). The wind tunnel has a closed-circuit arrangement with the 1.5 m x 2 m x 5 m (H, W, L) test section size capable of delivering the maximum airspeed of 80 m/s. Due to the test section size restriction that limits the model width to be under 1.5 meters, the experiment is conducted using the sub-scale force model with the 1:2.67 scaling factor. The wind tunnel model is fabricated in-house using the additive manufacturing machine followed by the hand surface finishing process. The structural integrity of the finished model is confirmed by the sandbag loading method which simulates the maximum lift condition. The aerodynamic forces and moments are measured by the six-component sting-type force balance which capable of 2669 N (normal force), 1334 N (axial force), 712 N (side force), 113 N-m (pitching moment), 56.5 N-m (yawing moment), and 56.5 N-m (rolling moment) maximum load limit. The model is attached to the balance unit using an offset type mounting to provide adequate clearance between the balance mounting system and the test model. The lift, drag, and pitching moment coefficients are at the angle of attack ranging from -5.0 to 15.0 degrees.
2.3 Aerodynamic characteristics Comparison

The comparison of the air vehicle's aerodynamic characteristics is illustrated in figure 4. The lift coefficient variation with angle-of-attack from all three approaches shown in figure 4 (a) is correlated well within the linear region ranging from -1.0 - 6.0 degree, in which the lift curve slope of 0.3 per degree is observed. The lift coefficient comparison between CFD and wind tunnel experiment shows a good correlation in which a slightly lower lift curve slope is observed from the CFD computational result.

![Figure 3.](image1)

![Figure 3.](image2)

Figure 3. (a) The tactical Solar Power UAV Model (b) The SRWT at NKRAFA

![Figure 4.](image3)

![Figure 4.](image4)

Figure 4. The Fundamental aerodynamics characteristics comparison
It is also observed that the critical angle-of-attack is similar between CFD and wind tunnel experiments. According to the data from the wind tunnel experiment, the air vehicle could achieve the maximum lift coefficient of 1.495 at 10 degrees angle of attack.

The drag coefficient variations versus angle-of-attack obtained from CFD and wind tunnel experiments, shown in figure 4(b), are well correlated with the minimum drag which is equal to 0.037 at -2 degrees angle-of-attack. The pitching moment coefficient variations with angle-of-attack shown in figure 4(c) show that, despite the negative pitching moment tendencies which indicated that the design has favorable 'positive' static longitudinal stability, there is no correlation between CFD and wind tunnel experimental results. This is due to the effect of the model installation mounting arrangement which gives a large vertical separation between the model's center of gravity and the balance's electrical measurement center. Figure 4 (d) illustrates the lift-to-drag ratio variation with angle-of-attack. It is observed that the air vehicle could achieve maximum aerodynamic efficiency at 2.0-degree angle-of-attack with the maximum lift to drag ratio of 20.05.

3. Stability and control

The stability and control characteristics of the air vehicle could be determined by various approaches such as (i) empirical calculation and simulation [7-9], (ii) wind-tunnel testing [10], and (iii) flight testing [10]. In the early design stage, an empirical calculation and simulation are commonly employed as it could provide some advantages in terms of engineering effort and resource requirements while delivering reasonable results [11-12]. In this design study, the XFLR5 software tool is implemented to determine the static and dynamic stability and control of the solar-UAV design. The data from table 1 is used as input parameters for XFLR5 calculations based on the design flight conditions. The mass properties of the airframe and subsystems arrangement are illustrated in figure 5. The calculation output expressed as longitudinal and lateral-directional stability derivatives are illustrated in table 2 and table 3, respectively. Note that all values are expressed in per-radian.

![Figure 5. Weight and Balance model in XFLR5 for stability and control derivatives calculation](image-url)
Table 2. Longitudinal stability and control derivatives

| Derivative | Value |
|------------|-------|
| $C_{Xu}$   | $-0.0469$ |
| $C_{Xe}$   | $0.53020$ |
| $C_{mu}$   | $-0.0043$ |
| $C_{me}$   | $-0.3423$ |
| $C_{ma}$   | $-13.937$ |
| $C_{mδ}$   | $-1.0304$ |
| $C_{zu}$   | $0.00610$ |
| $C_{ze}$   | $5.50370$ |
| $C_{zq}$   | $6.08290$ |
| $C_{zδ}$   | $0.00150$ |

Table 3. Lateral-Directional stability and control derivatives

| Derivative | Value |
|------------|-------|
| $C_{Yβ}$   | $-0.13613$ |
| $C_{Yp}$   | $-0.15746$ |
| $C_{Yr}$   | $0.125480$ |
| $C_{lβ}$   | $-0.06683$ |
| $C_{lp}$   | $-0.62025$ |
| $C_{lr}$   | $0.198220$ |
| $C_{lδ}$   | $0.013120$ |
| $C_{nβ}$   | $0.029971$ |
| $C_{np}$   | $-0.10014$ |
| $C_{nr}$   | $-0.02526$ |
| $C_{ng}$   | $-0.04225$ |
| $C_{ngδ}$  | $0.00150$ |

3.1. Static stability

As stated in the UAV airworthiness certification guidelines [13-14], the air vehicle should be demonstrated that the stability characteristics in all axes are positive. The static stability is crucial as the aircraft cannot be dynamically stable without being statically stable. Using the XFLR5 as an analysis tool it is confirmed that the solar-powered UAV design concept possesses positive static stability in longitudinal, lateral and directional axes as it gives negative pitching moment curve slope, positive yawing moment curve slope, and negative rolling moment curve slope. This would ensure that the aircraft's initial tendency to respond back to the equilibrium state once being disturbed by vertical and lateral gusts.

3.1.1. CG location variation

The location of the center of mass is an important factor affecting the aircraft’s stability and control characteristics. Based on the airframe mass estimation and the expected arrangement of subsystem components defined at the conceptual design phase, the center of mass of the aircraft is located at the distance of 37.88% of the wing mean aerodynamic chord measured longitudinally from the leading edge of the wing at constant chord section. As the aircraft's static longitudinal stability characteristic is determined from the position of an aircraft's center of mass and its aerodynamic center along the longitudinal axis, it is important to determine the neutral point which considered as a center of mass location where the aircraft possess neutral static longitudinal stability. A sensitivity study to observe the pitching moment coefficient curve slope $ZX$ variations due to the changes in the center of mass position is performed. Based on the sensitivity data shown in figure 6, the neutral point of the solar-powered UAV is determined at the distance of 12.2 cm measured longitudinally from the wing leading edge at the constant chord section. Finally, the aircraft's static margin could be calculated based on the wing mean aerodynamic chord and the longitudinal position of the aircraft's center of mass and aerodynamic center.

$$K_n = \frac{x_{NP}-x_{CG}}{c}$$ (1)
Where $X_{NP}$ is the position of the neutral point, $X_{CG}$ is the position of the CG, $c$ is the mean aerodynamic chord, and $K_r$ is the static margin. It is observed that the solar-powered UAV design concept has a static margin value of 7.24%, which is considered moderate.

![Figure 6. Sensitivity Analysis of CG variation and Neutral Point Determination](image)

### 3.2. Dynamic stability

In addition to the static stability, the aircraft is also required to be dynamically stable to achieve favorable flying quality. To observe the dynamic stability characteristics, the equation of motion in six degrees of freedom (6DOF) of the solar-powered UAV is linearized using the small disturbance theory around the trim flight condition. The linearized equation of motion for the longitudinal axis is expressed as

$$
\begin{bmatrix}
\Delta \dot{u} \\
\Delta \dot{\omega} \\
\Delta \dot{q} \\
\Delta \dot{\theta}
\end{bmatrix} =
\begin{bmatrix}
X_u & X_w & 0 & -g \\
Z_u & Z_w & u_0 & 0 \\
M_u + M_w Z_u M_u + M_w Z_w M_q + M_w u_0 & 0 & 0 & \Delta \theta \\
0 & 1 & 0 & 0
\end{bmatrix}
\begin{bmatrix}
\Delta u \\
\Delta w \\
\Delta q \\
\Delta \theta
\end{bmatrix}
+ \begin{bmatrix}
X_{\delta_e} & X_{\delta_T} \\
Z_{\delta_e} & Z_{\delta_T} \\
M_{\delta_e} + M_w Z_{\delta_e} M_{\delta_T} + M_w Z_{\delta_T} & 0 \\
0 & 0
\end{bmatrix}
\begin{bmatrix}
\Delta \delta_e \\
\Delta \delta_T
\end{bmatrix}
$$

(2)

and for the lateral-directional axis

$$
\begin{bmatrix}
\Delta \dot{v} \\
\Delta \dot{p} \\
\Delta \dot{r} \\
\Delta \phi
\end{bmatrix} =
\begin{bmatrix}
Y_v & Y_p - (u_q - Y_r) g \cos \theta_0 \\
L_v L_p & L_r & 0 & \Delta \phi \\
N_v N_p & N_r & 0 & \Delta \theta \\
0 & 1 & 0 & 0
\end{bmatrix}
\begin{bmatrix}
\Delta v \\
\Delta p \\
\Delta r \\
\Delta \phi
\end{bmatrix}
+ \begin{bmatrix}
0 & Y_{\delta_r} \\
L_{\delta_a} L_{\delta_r} & 0 \\
N_{\delta_a} N_{\delta_r} & 0 \\
0 & 0
\end{bmatrix}
\begin{bmatrix}
\Delta \delta_a \\
\Delta \delta_r
\end{bmatrix}
$$

(3)

where $x_{Long} = [\Delta u \Delta w \Delta q \Delta \theta]^T$ is the longitudinal state vector and $x_{Lat} = [\Delta v \Delta p \Delta r \Delta \phi]^T$ is the lateral-directional state vector. The input vectors in the longitudinal and lateral-directional axis are expressed as $u_{Long} = [\Delta \delta_e \Delta \delta_T]^T$ and $u_{Lat} = [\Delta \delta_a]^T$. respectively. The $\Delta u, \Delta v, \Delta w$ represent linear velocities along x-axis, y-axis, and z-axis, and $\Delta p, \Delta q, \Delta r$ represent angular velocities about the x-axis, y-axis, and z-axis. The pitch and bank attitude are represented by $\Delta \theta$ and $\Delta \phi$, respectively. Other parameters in the square brackets are the dimensional stability and control derivatives which are derived from table 2 and table 3. The mathematical model is implemented in the Scilab/Xcos dynamic system modelling framework.
3.2.1 Longitudinal dynamic stability

The open-loop dynamic longitudinal stability characteristics of the solar-powered UAV is obtained by solving equation (2) subjected to the fixed control inputs assumption. By establishing the initial steady-state level-flight condition at 9.45 m/s airspeed and 500 m flight altitude, the aircraft is shown to have stable phugoid as well as short period motion after being disturbed by an external gust representing as a singlet (non-cyclic) external pulse. Table 4 illustrated the longitudinal motion characteristics of the solar-powered UAV design. The open-loop dynamic response of the aircraft along the longitudinal axis is illustrated in figure 8.

| Characteristic roots | Phugoid | Short period |
|----------------------|---------|--------------|
| $-0.08154 \pm 0.5954\iota$ | $-8.134 \pm 3.546\iota$ |
| $\omega_n$ (rad/s) | 0.108 | 0.916 |
| $\zeta$ | 0.096 | 8.816 |

The responses of the phugoid motion expressed by variables $\Delta u, \Delta \theta, \Delta \alpha$. is plotted as illustrated in figure 8 (a)-(c) in which $\Delta \alpha$ is derived from $\Delta \omega$, indicating the aircraft’s Phugoid motion is lightly damped in which the oscillation would converge and fully settled within 90 seconds. The short-period longitudinal responses are plotted as illustrated in figure 8 (d)-(f), which shows the highly-damped oscillatory motion with settling time equal to 1.0 second. This confirms the aircraft’s stable longitudinal dynamic stability under the specified flight speed and altitude with the stick-fixed condition.

Figure 8. The Open-loop longitudinal dynamic response, Phugoid (a) – (c) and Short Period (d) – (e)

3.2.2 Lateral- Directional dynamic stability
Similar to the longitudinal stability analysis, the open-loop lateral-directional dynamic stability characteristics of the solar-powered UAV is obtained by solving the equation (3). Subjected to the same steady-state flight condition used in a longitudinal case, a singlet external disturbance is generated to introduce a sideslip resulting in a small bank angle $\Delta \phi$. The lateral-directional dynamic response of the aircraft in pure rolling and roll-yaw coupling (dutch-roll and spiral) motions are observed. Figure 5 illustrates the characteristic roots, natural frequencies, damping ratio, and time constant of all three motions are illustrated in Table 5.

| Table 5. The UAV Lateral-directional motion characteristics |
|-----------------------------------------------------------|
| Characteristic roots | Dutch roll | Roll | Spiral |
| $\omega_n$ (rad/s) | $-1.044 \pm 2.721i$ | -28.67 | 0.1505 |
| $\zeta$ | 0.389 | - | - |
| Time constant (sec) | - | 0.348 | 4.607 |

As illustrated in figure 9, the time history of the aircraft response in dutch-roll motion, considering motion variables $\Delta \rho, \Delta r, \Delta \phi$, indicates the convergent oscillation behaviour in which the aircraft returns to its trim bank angle after 10 seconds. It is also observed that for pure rolling motion, the aircraft response with a stable roll motion with time constant equal to 0.348 seconds and returns to its trim bank angle within 1.74 seconds.

3.3. Control of UAV

The UAV has three aerodynamic control surfaces consist of ailerons and ruddervator (the combination of the solar-powered UAV concept employing ailerons for roll control). As the empennage design of the aircraft is of the V-tail type, the ruddervator coupling control surface system is implemented for both roll and yaw control of the aircraft. An overview of the control surface arrangement is illustrated in figure 10. The aileron is designed with a constant-chord distribution along with the outboard wing panel. Table 6 shows the geometric parameters of the aileron including chord ratio, span-wise location of the aileron's inboard and outboard end, and the design deflection angles. The rate of change of pitching moment due to elevator deflection (pitch control power) and the rate of change of yawing moment due to rudder deflection (yaw control power) are estimated at -1.030/rad and 0.04224/rad, respectively.
Figure 10. The UAV primary control surfaces, ailerons and ruddervator

Table 6. The ailerons geometric data

| $c_a/c$ | $b_{l/2}$ | $b_{o/2}$ | $\delta_{\alpha_{max}}$ (degree) |
|--------|-----------|-----------|-------------------------------|
| 0.3    | 0.44      | 1.0       | up                            |
|        |           |           | down                          |
|        |           |           | 20                            |
|        |           |           | 20                            |

4. Conclusion
In this paper, the fundamental aerodynamic characteristics, as well as the stability and control of the solar-powered UAV, are investigated at the design flight conditions using various methods. The fundamental aerodynamic characteristics obtained from CFD and wind tunnel testing are compared for validation. The stability and control characteristics obtained from XFLR5 software shows that solar power UAV is flyable. However, to complete the preliminary design phase the performance and structural analyses need to be performed. Moreover, after the preliminary design of the solar-powered UAV is completed the detailed design needs to be conducted before the prototype could be fabricated. Then the ground and flight-testing program could be established to verify the aircraft's flight performance as well as its flying qualities.

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