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To cite this article: E. Irsyad Lukman and M. Agoes Moelyadi 2018 J. Phys.: Conf. Ser. 1005 012050

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Longitudinal Static Stability and wake visualization of high altitude long endurance aircraft developed in Bandung institute of technology

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Abstract. A High Altitude Long Endurance (HALE) Unmanned Aerial Vehicle (UAV) is currently being researched in Bandung Institute of Technology. The HALE is designed to be a pseudo-satellite for information and communication purpose in Indonesia. This paper would present the longitudinal static stability of the aircraft that was analyzed using DATCOM as well as simulation of the wing using ANSYS CFX. Result shows that the aircraft has acceptable stability and the wake from the wing at climbing condition cannot be ignored, however it does not affect the horizontal tail.

Nomenclature

\( \rho \) : Fluid Density, \( S_M \) : Momentum Source Components

\( t \) : Time, \( S_E \) : Energy Source Components

\( U \) : Velocity Vector, \( \lambda \) : Thermal Conductivity

\( p \) : Pressure, \( h_{\text{tot}} \) : Total Enthalpy

\( \tau \) : Stress Tensor, \( T \) : Temperature

1. Introduction

In recent decades, the use of Unmanned Aerial Vehicles (UAV) in military applications has increased. The potential to substitute satellite to High Altitude Long Endurance (HALE) as a relay for communications is one such applications[1]. ITB is currently being supported by Direktorat Riset Teknologi dan Pendidikan Tinggi (RISTEKDIKTI) in doing research and development of this type of aircraft. The aircraft that was analyzed in this paper is the second prototype that was made. The first prototype had four propulsion systems and was made mainly of balsa wood. However, after the structural failure of the first prototype, the second one was made mainly by carbon fiber composite.
In addition to that, the second prototype seeks to reduce the number of propulsion system to save weight and improve stability. The design also reduces the number of tail section as can be seen from Figure 1 and Figure 2 in order to reduce drag while increasing wingspan to generate more lift. The other improvement is that this second prototype will be using solar panels to generate power during the day. However, this paper only discuss about the wake analysis from the wing, and longitudinal static stability of the aircraft.

![Figure 1 First Prototype of ITB HALE UAV](image1)

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![Figure 2 Second Prototype of ITB HALE UAV Design](image2)

| Specification    | Value |
|------------------|-------|
| MTOW [kg]        | 20    |
| Wingspan [m]     | 16    |
| MAC [m]          | 0.4   |
| Aspect Ratio     | 40    |

Even though this aircraft uses natural laminar airfoil EMX 07, it was expected that the aircraft would need a high angle of attack during climbing and this would provide the motivation to check the validity of inviscid assumptions. When the flow over the airfoil is dominated by viscous effect, then the boundary layer at the top would likely separate and form a large wake downstream $^2$. This wake may affect the airflow near the tail $^3$. Generally, the inviscid assumptions hold for high Reynolds number hence to simplify the problem, the CFD simulation was made at atmospheric condition at operating altitude where the density is lower. Since Reynolds number is related to density, this simplification would give a conservative result.

Lastly, longitudinal static stability will be analyzed using the software DATCOM on the final configuration of the aircraft. The static stability parameters and its derivative are taken from the output and the value will be crosschecked from theory to determine whether the aircraft is stable or not.
2. Methodology

2.1 Aircraft Overview

The aircraft cruising speed is 16 m/s with wing geometry as shown in Figure 3 (all dimensions in mm). It will operate at 5 km above sea level and the atmospheric properties would refer to International Standard Atmosphere\(^4\). The simulation would be done by varying the angle of attack to 0, 5, and 10 degrees.

![Figure 3 Second Prototype Dimensions](image)

2.2 ANSYS CFX Solver

The equations that was used in ANSYS CFX solver is the unsteady Navier-Stokes equations in conservation form\(^5\). Below is presented the continuity equation, momentum equation, and total energy equation that was used by ANSYS CFX.

\[
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{U}) = 0
\]

\[
\frac{\partial (\rho \mathbf{U})}{\partial t} + \nabla \cdot (\rho \mathbf{U} \times \mathbf{U}) = -\nabla p + \nabla \cdot \mathbf{\tau} + S_M
\]

\[
\frac{\partial (\rho h_{tot})}{\partial t} + \nabla \cdot (\rho U h_{tot}) = \nabla \cdot (\lambda \nabla T) + \nabla \cdot (U \cdot \mathbf{\tau}) + U \cdot S_M + S_E
\]

In order to solve this equation a fluid domain that was discrete must be created. The discretization process was called meshing and for this simulation, a structured mesh was created. The resulting mesh can be seen in the Figure below. Next, boundary and initial condition must be defined to initiate the simulation. In this simulation the wing is defined as a no slip wall where the velocity at the wall is zero, and the fluid is assumed to be incompressible.
2.3 Stability Parameters and DATCOM

An aircraft is said to be stable if the response of the aircraft due to small disturbance is to return to its original state \[^{[6]}\]. To quantify this condition some aerodynamic parameters must be considered. These parameters were derived from an equilibrium equation where the aircraft was in trim condition \[^{[7]}\].

Referring to the Figure above, the equilibrium equation is

\[
T \cos(\alpha + \tau) - D - mg \sin \gamma = 0
\]
\[
-T \sin(\alpha + \tau) - L + mg \cos \gamma = 0
\]
\[
M_A + M_T = 0
\]

where \(M_A\) denotes the moment due to aerodynamic forces and \(M_T\) the moment due to thrust.

Using some assumptions and non-dimensional conversion (details can be read from the references) it can be derived that if there are changes in the value of the variables in the equation, the aircraft would return to its equilibrium state if the conditions below is satisfied.

a. The change of pitching moment due to elevator deflection \(C_{m \delta e} < 0\)

b. The change of pitching moment due to angle of attack \(C_{m \alpha} < 0\)

The software that was used to find out the value of these parameters is DATCOM. DATCOM uses a semi-empirical approach by interpolating results from known parameters in a specific aircraft. The figure below shows the geometry that was generated to be analyzed in DATCOM.
3. Results and Discussions

3.1. Wake Visualization

Figure 6 Geometry Created in DATCOM

Figure 7 Stream Velocity Contour. (From Top to Bottom 0°, 5°, and 10°)
Figure 7 above shows the wake from the wing at different angle of attack. It can be seen that at 5° angle of attack the boundary layer thickens (shown by the white color at the upper surface of the wing in Figure 8), and at 10° angle of attack separation had already occurred at the thickest point of the airfoil. This shows that the wake produced when the aircraft was climbing (where the angle of attack is around 5°) can alter the flow downstream of the wing. However, the final configuration has horizontal tail placement that was not affected by the wake from 5° angle of attack.

Figure 8 Boundary Layer Comparison (0° top and 5° bottom)

3.2. Stability Results

The Figure above shows the curve that is taken from DATCOM output. The left figure show that $C_{m\alpha}$ of the HALE is negative, which means if the angle of attack of the aircraft is increased, it will have a tendency to pitch down and vice versa. This is an indication that the aircraft is stable.

The right figure shows the output from DATCOM, which is the increment of pitching moment coefficient due to elevator deflection. Hence, to obtain the $C_{m\delta_{e}}$ parameter, an integration of the curve
must be carried out[8]. By using trapezoidal method, it is obtained that the $C_{m_{de}} = -0.05$, which also indicates that the aircraft is stable.

4. Concluding remarks
The current design of the HALE prototype has good longitudinal static stability and the wake from the wing has been simulated to prove that it will not hinder the performance of the horizontal tail. However, flight test must be conducted to ascertain the result of analysis.

Acknowledgement
This research was supported by ITB and Direktorat Riset Teknologi dan Pendidikan Tinggi (RISTEKDIKTI).

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