Prediction of static stability in tandem wing unmanned aerial vehicle

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Abstract. The development of tube-launched folding wing UAV has become current interest and accordingly static stability analysis of this UAV would be necessary. The objective of this paper is to conduct a study to evaluate static stability of tube launched tandem wing UAV at its cruise condition. Computational fluid dynamics (CFD) using ANSYS CFX is conducted to acquire forces and moments acting on the UAV at various angles of attack and sideslip angles. Furthermore, static stability parameters such as $C_m$, $C_L$, $C_l$, $C_n$, and $C_Y$ are determined from the forces and moments obtained previously. The result indicates that the ITB tandem wing UAV complies the static stability criteria at its cruise condition.

1. Introduction
As unmanned aerial vehicles (UAV) become more popular in recent years, the development of UAV for further usability becomes more interesting [1]. Tube-launched folding wing UAV is among the new UAV technology being developed. This UAV has an unusual aircraft configuration such as foldable tandem wing as its main lifting surfaces. Among current technologies of UAV, tube-launched folding wing UAV excels in that the UAV requires smaller space due to its foldability, faster and easier take off using its tubular launcher, and no need take-off runway [2]. This UAV has a great potential in military and civil applications to perform mission such as monitoring, remote sensing, payload delivering and many others due to its distinct advantages.

In order to have a good and easy UAV control in performing missions, it requires a good stability performance. The value of $C_m$, $C_L$, $C_l$, $C_n$, and $C_Y$ as static stability parameters will show whether the UAV design satisfies a good static stability or needs an improvement.

For an object having more difficult geometry, the use of analytical method for solving the fundamental equations of fluid dynamics is not only ineffective but also impractical [3]. Experimental method, although may give an accurate result, is undermined due to its high cost and time [4]. In this case the numerical method is chosen instead. There are many software that could perform stability analysis such as XFLR, Datcom, and ANSYS CFX. XFLR will do the simulation using lifting line theory and can only simulate a simpler geometry [5]. While Datcom refers to experimental data and interpolate them as the result [6]. Due to the complexity of the UAV’s geometry, the authors choose to perform stability analysis using ANSYS CFX which will have better accuracy by simulating the whole complex UAV body and solving the unsteady Navier-Stokes equation in their conservation form. Kim et al has performed stability analysis of full geometry aircraft through CFD and response surface method [4]. Mahdi and Elhassan also calculate stability derivatives of an aircraft through the use of CFD [7]. Both authors states that CFD have proven to be effective in predicting stability characteristics of an aircraft.
2. UAV configuration

The full geometry aircraft model used in this study consists of canard (front lifting surface), wing (rear lifting surface), dual vertical tail, and electric pusher propulsion [8]. The UAV should fit inside a 6-inch diameter tubular launcher. Consequently, the chord length is constrained by the tube. To compensate the limited chord, the front lifting surface is designed to have long enough span so that it can produce sufficient lift for the UAV at cruise condition with desirable speed. For this short chord and long span lifting surface configuration, the tandem-wing layout is chosen [9]. The rear lifting surfaces has a longer span than the front lifting surfaces to achieve the aircraft aerodynamic centre rearward. Moreover, the UAV is also designed to have dual vertical tail to produce higher lateral-directional stability.

![Figure 1. Folding wing UAV [8]: (a) folded condition, (b) transition, (c) expanded condition.](image)

| Definition                        | Value       |
|----------------------------------|-------------|
| Altitude                         | 100 m       |
| Length \(L\)                     | 1124 mm     |
| Chord Length \(c1\)              | 100 mm      |
| Chord Length \(c2\)              | 100 mm      |
| Canard Span \(b1\)               | 1318 mm     |
| Wing Span \(b2\)                 | 1508 mm     |
| Vertical Stabilizer \(h\)        | 300 mm      |
| Canard-Wing LE distance \(d\)    | 635 mm      |
| Distance among Vertical stabilizers | 118 mm   |
| Canard Airfoil                   | NACA 8408   |
| Wing Airfoil                     | NACA 8408   |
| Vertical Stabilizer Airfoil      | NACA 0010   |
| MTOW                             | 3 kg        |
| Cruise Speed                     | 25 m/s      |
| \(S\) ref                        | 0.269 m\(^2\) |

Because the wing and canard must be foldable, the left and right segments of the lifting surfaces (wing and canard) are joined to the folding mechanism at different level, meaning that one segment is higher than the other. Consequently, there are two possible variations in placing the lifting surfaces [8]. The tandem wing UAV investigated in this paper uses the configuration which places the left canard higher than the right canard and the left wing lower than the right wing. This configuration is better than the other [8].
3. Numerical simulation method

The numerical simulations are performed using ANSYS CFX. The simulations are used to calculate the forces and moments acting on the UAV and are performed on several chosen angles of attack and side slip angles.

The set of equations solved by ANSYS CFX are the unsteady Navier-Stokes equations in their conservation form. The instantaneous equation of mass, momentum, and energy conservation can be written as follows in a stationary frame [10]:

Continuity equation
\[ \frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{U}) = 0 \]  (1)

Momentum equation
\[ \frac{\partial (\rho \mathbf{U})}{\partial t} + \nabla \cdot (\rho \mathbf{U} \times \mathbf{U}) = -\nabla p + \nabla \cdot \mathbf{\tau} + S_M \]  (2)

Thermal energy equation
\[ \frac{\partial (\rho h_{tot})}{\partial t} + \nabla \cdot (\rho \mathbf{U} h_{tot}) = \nabla \cdot (\lambda \nabla T) + \nabla \cdot (\mathbf{U} \cdot \mathbf{\tau}) + \mathbf{U} \cdot S_M + S_E \]  (3)

In order to form a closed system, those equations above need to be augmented with constitutive equations of state, which for ideal gas the equations of state are:
\[ \rho = \frac{\omega p_{abs}}{R_0 T} \]  (4)
\[ dh = c_p dT \]  (5)

The fluid domain has a C-shape and its maximum length is approximately 110 times the chord. The number of nodes used is \(7.5 \times 10^5\) with the number of elements is \(3.3 \times 10^6\). The computational domain and mesh are shown in the figure below.

Figure 2. Wing and canard placement configuration [8].

Figure 3. Meshing for simulation.
4. Static stability parameters

Static stability is the tendency of the aircraft to develop forces or moments, on its own, which directly oppose an instantaneous disturbance of a motion variable, from a trimmed (steady state) flight condition [11].

The longitudinal static stability is achieved when the change of pitching moment due to angle of attack is below 0 ($C_{m_{\alpha}} < 0$). This means that for a positive $\alpha$ disturbance, the aircraft should naturally produce a negative M opposing the $\alpha$. $C_{m_{\alpha}} < 0$ is the main requirements for longitudinal static stability [12]. In addition, $C_{L_{\alpha}} > 0$ may also indicate longitudinal static stability for an aircraft having center of gravity in front of the aircraft aerodynamic center.

![Figure 4. Longitudinal static stability illustration.](image)

In a similar way, the main conditions for lateral-directional static stability are $C_{l_{\beta}} < 0$ and $C_{n_{\beta}} > 0$ meaning that for a positive $\beta$ disturbance, the aircraft should naturally produce a negative roll moment L (rolling to the left from the pilot’s standpoint) and a positive yaw moment N (yawing to the right from the pilot’s standpoint) opposing the $\beta$. $C_{l_{\beta}} < 0$ is also an indication of aircraft lateral-directional static stability.

![Figure 5. Lateral–directional static stability illustration.](image)

5. Results and discussion

The CFD simulations yielded the value of forces and moments acting on the UAV. The non-dimensional coefficient $C_m$ (pitching moment coefficient), $C_L$ (lift coefficient), $C_l$ (rolling moment coefficient), $C_n$ (yawing moment coefficient), and $C_Y$ (side force coefficient) can be extracted from the forces and moments using the following equations
The resulting values of $C_m$ and $C_L$ at various angles of attack are presented below.

![Figure 6. $C_m$ vs $\alpha$.](image)

The results above show that as the angle of attack is increasing, the value of pitching moment coefficient ($C_m$) is decreasing and the value of lift coefficient is increasing. Using linear regression, the
value of $C_{m_a}$ is -0.04 and the value of $C_{L_{a}}$ is 0.1007 in the linear region. As discussed before, $C_{m_a} < 0$ and $C_{L_{a}} > 0$ indicate that the UAV have a good longitudinal static stability.

Likewise, the resulting value of $C_{i}$, $C_{n}$, and $C_{Y}$ at various side slip angle are shown below.

As the sideslip angle $\beta$ increases, the values of $C_i$ and $C_Y$ decrease while the values of $C_n$ increase. Using linear regression, the value of $C_{l_{\beta}}$ is -0.0194, the value of $C_{y_{\beta}}$ is -0.0077 and the value of $C_{n_{\beta}}$ is 0.02. This means that as the disturbance $\beta$ increases, the aircraft will naturally produce negative rolling
moment increment and positive yawing moment increment to counter the increasing $\beta$. Moreover, positive increase in the value of side force coefficient is also a good sign of lateral-directional static stability as discussed before.

6. Concluding remarks
The resulting values of $C_{ma} = -0.04 < 0$ and $C_{la} = 0.1007 > 0$ indicates that the UAV has a good longitudinal static stability. Likewise, the values of $C_{l\beta} = -0.0194 < 0$, $C_{\gamma\beta} = -0.0077 < 0$ and $C_{n\phi} = 0.02 > 0$ indicate that the UAV has lateral-directional static stability. As a result, the ITB tandem wing UAV complies the static stability criteria at its cruise condition.

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