Effect of Rear Propeller, Canard, and Center of Gravity on Longitudinal Stability of High Altitude Long Endurance UAV flower-like Morphologies

Kevin Setiawan , Rio Rheza Harris , Marshell Antonius, Mochammad Agoes Moelyadi
Department of Aeronautics and Astronautics, Faculty of Mechanical and Aerospace Engineering, ITB
E-mail: kevinsetiawan@outlook.com, riorhezaharris@gmail.com, marshell18@students.itb.ac.id, moelyadimochammad@gmail.com

Abstract : The application of HALE (High Altitude Long Endurance) UAV (Unmanned Aerial Vehicle) to address the challenge of 3D (Dull, Dirty, Dangerous) missions has received a considerable attention from many researchers and aircraft developers. To fulfill the challenge of its mission, the UAV must be designed to have high efficiency aerodynamic and propulsion system with a lightweight structure. The position of propeller in an above-wing-mounted engine plays a vital role in providing efficient aerodynamic and propulsion. The use of ANSYS 15.0 software to simulate interaction between wing platform and propeller position on HALE UAV flight condition can determine the most appropriate propeller position in terms of aerodynamic and propulsion efficiency. The simulation result will give comparison of aerodynamic characteristic of interaction between wing platform and various propeller position and therefore the most appropriate propeller position.
Key Words : HALE UAV, propeller position, aerodynamic characteristic

Nomenclatures

R : location of center of gravity
M : total mass of all component,
m : mass of each component
R : length between component center of mass and reference point.
L : Lift
D : Drag
M : Moment
CL : Lift coefficient
CD : Drag coefficient
CM : Pitching Moment coefficient
P : density
V : velocity
S : wing area

1. Introduction

Unmanned aerial vehicles (UAVs) are defined as aerial vehicles that do not have human operator on it.They can fly autonomously by autonomous control system or be piloted by remote control. The first UAV development dated back to the Persian Gulf War which is driven by military needs. However, nowadays, it result in civilian missions such as area surveillance for hard-to-reach place or for doing trivial task such as delivering item which Amazon does or taking a photo.

Nowadays, the majority of the HALE UAVs that have been developed many use wing tails for aircraft stability reason such as Qinetiq Zephyr[1)], X-HALE, SoLong and Sunrise, however some of them have being developed without tail. To ensure the stability of a tailless UAV, canard can be propose as an alternative to replace tail function., especially on a propeller-driven HALE UAV. The canards may be positioned in front of the wing nose and propeller to produce stabilityeffects. How much stability effect can be produced by canard, if the size and position of canard affects the aircraft stability ? Snorri Gudmundsson[1] explain that canard can be used in exchange of horizontal tail for maintaining the longitudinal stability of the aircraft. Mohd Alli, et.al[2)] explain that canard can affect the lift coefficient, increasing drag and improve the stability of the aircraft

This paper focuses on finding the effect of canard positioned in front of the wing nose and propeller on HALE UAV stability using computational fluid dynamics approach. The canard used will be varied in term of span size (constant aspect ratio) and relative position to the wing nose. The optimum position is decided by comparing the aerodynamics characteristic of each configuration.

2. HALE UAV Model

2.1. HALE UAV Model

The HALE UAV use a straight wing design with tailless configuration for subtituting the previous design with horizontal tailplane. This UAV will be powered by nine motor which positioned evenly divided along the wing. The HALE UAV model is shown on Fig. 2.1.1. The HALE UAV's wing use EMX 07 and the canard use NACA 0012 airfoil as shown in Fig. 2.1.2 and 2.1.3 respectively.

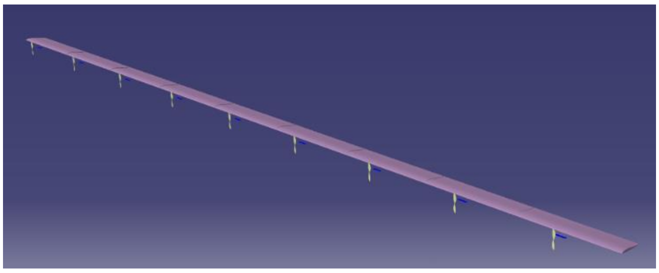

Fig. 2.1.1. Configuration model of HALE UAV

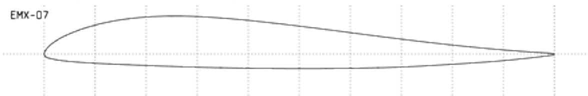

Fig. 2.1.2. Wing airfoil (EMX 07)[4]

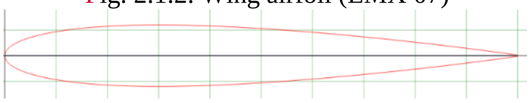

Fig. 2.1.3. Canard airfoil (NACA 0012)[3]

Table 2.1.1. HALE UAV dimension

Wing	
Airfoil Type	EMX-07
Chord (m)	0.6
Span Length	18
Propeller	
Diameter (m)	0.4
Rpm	3000
Position	0.4 m behind wing
Canard	
Airfoil	NACA 0012
AR	4
Span	0.3 m
Position	0.4 m in front of wing

Table 2.1.2. HALE UAV component weight

Component	Weight (g)
Wing	1200
Canard 10 cm span	5
Canard 20 cm span	20
Canard 30 cm span	45
Propeller and motor	63
Battery	197

The dimension that used above is acquired from the given Design Requirements and Objectives

2.2. Flight Operation Condition

For surveillance, the designed HALE UAV will fly at high altitude condition with the atmosphere conditions as follow:

Table 2.2.1. HALE UAV flight condition

Flight Condition	
Flight speed (m/s)	16
Altitude (feet)	20000
Temperature (K)	248.4
Pressure (Pa)	46650

2.3. Center of Gravity Position

To determine moment of the HALE UAV, first we must know the position of the center of gravity for each configuration. The center of gravity can be calculated by using the equation as given below :

$$\mathbf{R} = \frac{1}{M} \sum_{i=1}^{n} m_i \mathbf{r}_i, \tag{1.}$$

Position of center of gravity for each configuration given at table 2.3.1.

Table 2.3.1. HALE UAV configuration center of gravity position

Component	c.g. position (% chord)
Wing only	25
wing with prop	56
with 10 cm canard	8.44
with 20 cm canard	8.32
with 30 cm canard	8.15

2.4. Simulation Process

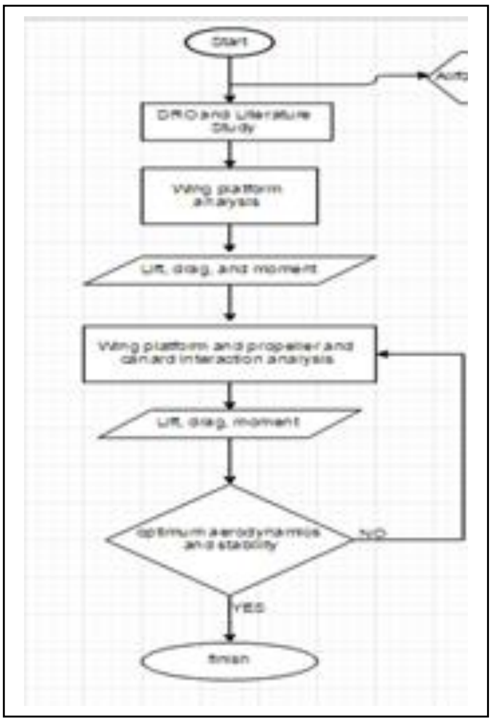

Fig. 2.4.1. Simulation and analysis procedure

Fig. 2.4.1. shows the flowchart of computation procedure for the HALE UAV. The determination of the UAV configuration based on the design requirement and objective (DRO). The EMX-07 airfoil, which categorized as a natural laminar flow airfoil, was selected due to its optimum characteristics for low speed. The simulation begins with the computation of the wing only and then followed by the combination of the wing and propeller in order to know its aerodynamic characteristics and at the end of the simulation, the canard model is included.

2.5. Aerodynamic Performance

The performance of HALE UAV can be evaluated by computing its aerodynamic forces (lift and drag) and moments. We can obtain this characteristics by simulating the designed HALE UAV using ANSYS ICEM CFD software. The equation for Lift, L, Drag, D and pitching moment, M are given as follows:

$$L = \frac{1}{2} x\, \rho\, x\, V^2 x\, S\, x\, C_L \qquad (2.)$$

$$D = \frac{1}{2} x\, \rho\, x\, V^2 x\, S\, x\, C_D \qquad (3.)$$

$$M = \frac{1}{2} x\, \rho\, x\, V^2 x\, S\, x\, C_M \qquad (4.)$$

3. Simulation Method

3.1. Governing Equation

Governing equation used by ANSYS ICEM CFX is Reynolds Averaged Navier-stokes including continuity, momentum and total energy equations as follows;

• The Continuity equation

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \boldsymbol{U}) = 0 \qquad (5.)$$

• The Momentum equation

$$\frac{\partial (\rho \boldsymbol{U})}{\partial t} + \nabla \cdot \left(\rho \boldsymbol{U} \otimes \boldsymbol{U}\right) = -\nabla p + \nabla \cdot \tau + \boldsymbol{S}_M \qquad (6a.)$$

where the stress tensor, τ , is related to the strain rate by

$$\tau = \mu \left(\nabla \boldsymbol{U} + (\nabla \boldsymbol{U})^T - \frac{2}{3} \delta \nabla \cdot \boldsymbol{U} \right) \qquad (6b.)$$

• The Total Energy Equation

$$\frac{\partial (\rho h_{\text{tot}})}{\partial t} - \frac{\partial p}{\partial t} + \nabla \cdot (\rho \boldsymbol{U} h_{\text{tot}}) = \nabla \cdot (\lambda \nabla T) + \nabla \cdot (\boldsymbol{U} \cdot \tau) + \boldsymbol{U} \cdot \boldsymbol{S}_M + \boldsymbol{S}_E \qquad (7a.)$$

where *h*tot is the total enthalpy, related to the static enthalpy *h*(T,P) by:

$$h_{\text{tot}} = h + \frac{1}{2} \boldsymbol{U}^2 \qquad (7b.)$$

The evaluation of turbulence viscous effect uses shear stress transport (SST)

3.2. Simplification of Simulation Model

In order to reduce computation time and memory used in the simulation, the model is simplified become one segment with span of 2 meter together with the propeller behind the wing and canard that positioned in front of and parallel to the wing as shown in Fig. 3.2.1. This simplification is carried out by applying symmetry boundaries at both ends of the wing.

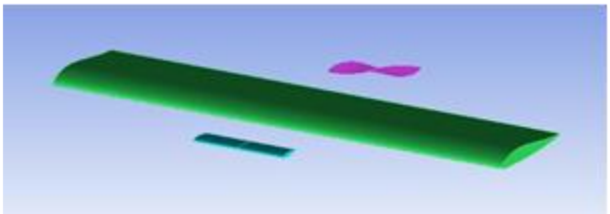

Fig. 3.2.1. Computational model of HALE UAV

3.3. Domain Computation and Mesh generation

The simulation uses three blocks of domain computation which consist of propeller domain, canard domain and the wing domain. The connection between domains uses interfaces. In order to recreate the effect of propeller rotation, the frozen model is used by rotating the air flow and making the propeller on stationary condition. Unstructured meshes which generated using Delaunay triangulation are used for meshing on boundary surfaces and inside the computational domains. In order to capture viscous effect near surface, the prism meshes close to the surfaces are generated.

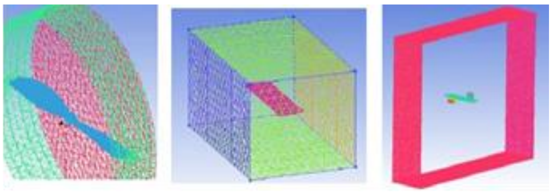

Fig. 3.3.1. Computational domains and generated meshes for propeller (left), canard (center), wing (right)

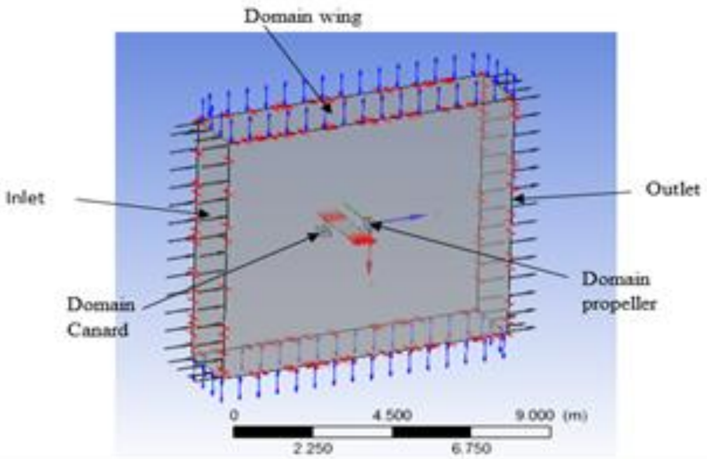

Fig. 3.3.2. Computational domain used in the simulation

Afterward, we start running the simulation with boundary condition set according to the flight condition such as pressure, temperature and flight speed. The domain includes Inlet, Outlet, Symmetry, Opening and Interface as shown in Fig. 3.3.2.

4. Result and Analysis

4.1. Aerodynamic Characteristics of Wing Only, With Propeller and Different Canard Size.

4.1.1. Lift Coefficient

Fig. 4.1.1.1. shows lift coefficients for clean wing, wing with propeller and additional canards with different span. The canard size varies in spans, namely 10 cm, 20 cm and 30 cm. The addition of propeller to the clean wing decrease the overall lift coefficient for every angle of attack. The addition of canard canard with longer span yields higher lift coefficient but still have lower value compared to the wing with propeller configuration. The zero lift coefficient of the wing, CL_0 is 0.097.

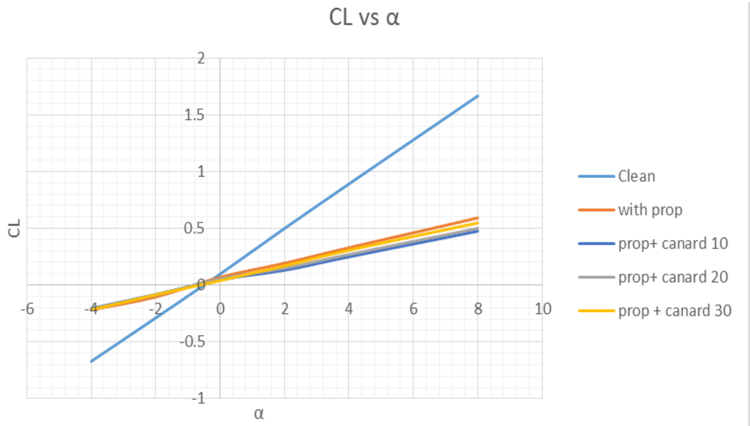

Fig. 4.1.1.1. Lift coefficient vs angle of attack comparison graph

4.1.2. Drag Coefficient

Comparison of drag coefficients between clean wing, wing with propeller and additional canards with different span configurations is shown Fig. 4.1.2.1. The addition of propeller to the clean wing increase drag coefficient with increasing angles of attack. The effect of canard with longer span (until 20 cm span) yields lower drag coefficient at low to moderate angles of attack compared to the wing with propeller configuration.

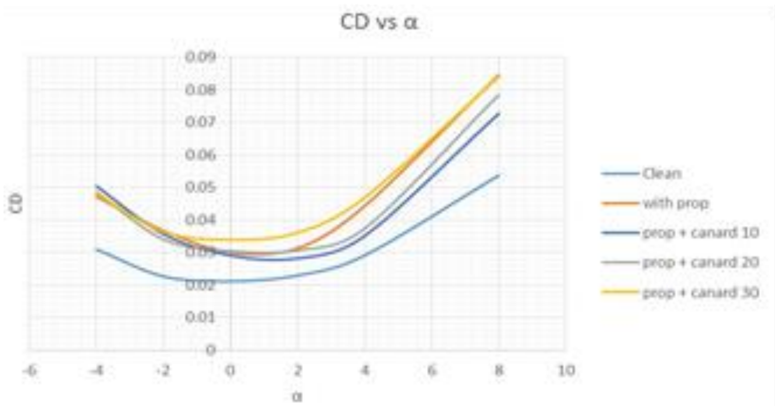

Fig. 4.1.2.1. Drag coefficient vs angle of attack comparison graph

4.1.3. Pitching Moment Coefficient

Fig. 4.1.3.1. shows comparison of pitching moment coefficients between clean wing, wing with propeller and additional canards with different spans. The configuration of wing only, wing with propeller, and wing with propeller and canard gives positive slope pitching moment coefficient with respect to angle of attack. This indicates that the configuration of the wing only, wing with propeller, and wing with propeller and canard yields unstable condition in longitudinal mode. From the result obtained, we can conclude that the use of canard is not a good alternative in this configuration to produce sufficient longitudinal stability.

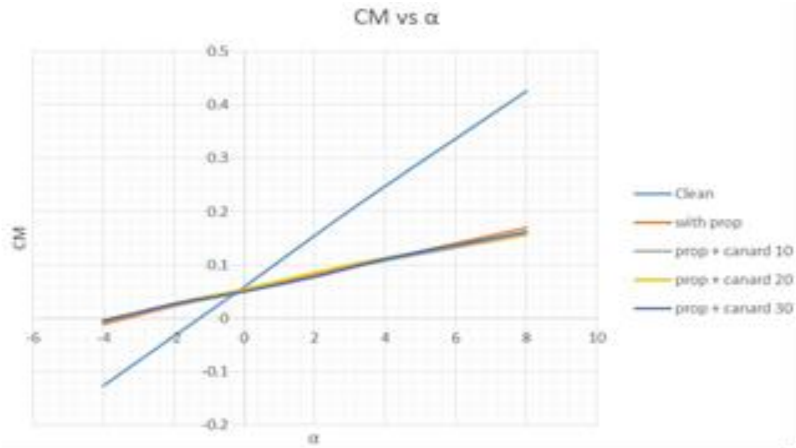

Fig. 4.1.3.1. Pitching moment coefficient vs angle of attack comparison graph

4.2. Alternative for Stabilizing the HALE UAV

4.2.1. Changing the Position of Center of Gravity

From the previous configuration we can tell that the center of gravity for the HALE UAV lies behind the aerodynamic center which lies on 25% chord length. To overcome instability in longitudinal direction, we move the battery as the power source for the propeller and motor system in front of the wing and the propeller is positioned 10 cm above the previous configuration to give a better aerodynamics performance as shown in Fig. 4.2.2.3. By moving the battery ahead of the wing, the distance between the wing and the canard become 0.7 m and the distance between the battery and wing is 0.4 m. By using this configuration, the center of gravity now lies in front of aerodynamic center. The location of center of gravity for the new configuration given in the table below.

Table 4.2.1.1. HALE UAV new configuration center of gravity position

Component	c.g. position (% chord)
Wing only	25
wing with prop	56
with 10 cm canard	8.44
with 20 cm canard	8.32
with 30 cm canard	8.15

4.2.2. Domain Computation and Mesh Generation

With the new configuration, there will be another addition for the battery domain. The same as the other domain, Delaunay triangulation are used for meshing on boundary surfaces and inside the computational domains. Afterwards, we start running the simulation with boundary condition set according to the flight condition such as pressure, temperature and flight speed. The domain includes Inlet, Outlet, Symmetry, Opening and Interface as shown in Fig. 4.2.2.2.

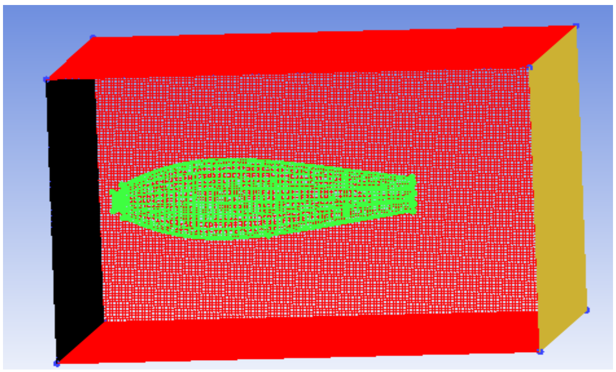

Fig. 4.2.2.1. Computational domain and mesh for the battery and its case

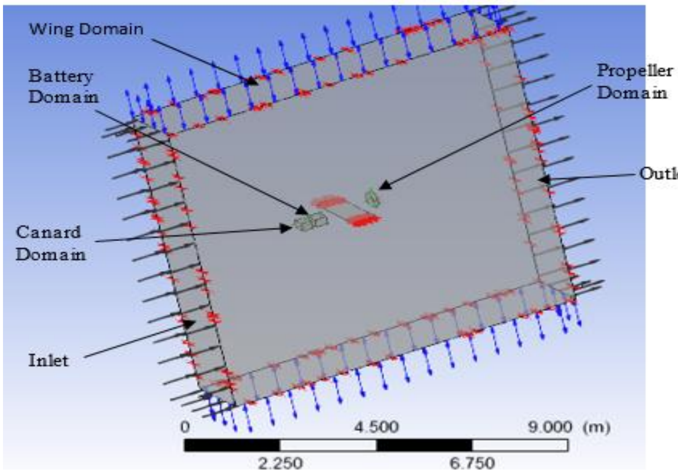

Fig. 4.2.2.2. New computational domain used in the simulation

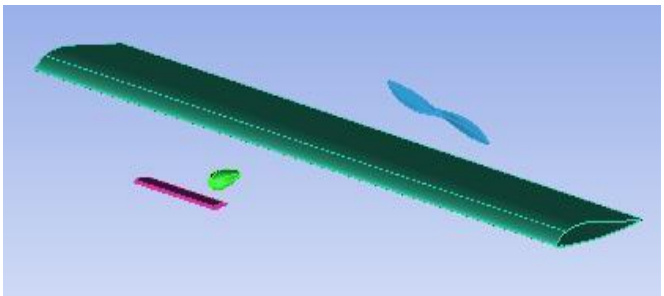

Fig. 4.2.2.3. Computational model of HALE UAV with new configuration

4.3. Aerodynamic characteristics of wing only, with propeller and different canard size in new configuration.

4.3.1. Lift Coefficient

Fig. 4.3.1.1. shows lift coefficients for clean wing, wing with propeller and additional canards in new configuration with different span. The canard size varies in spans, namely 10 cm, 20 cm and 30 cm. The addition of canard in new configuration with longer span produces higher lift coefficient especially for the 30 cm span canard addition which lift coefficient surpass wing with propeller configuration.

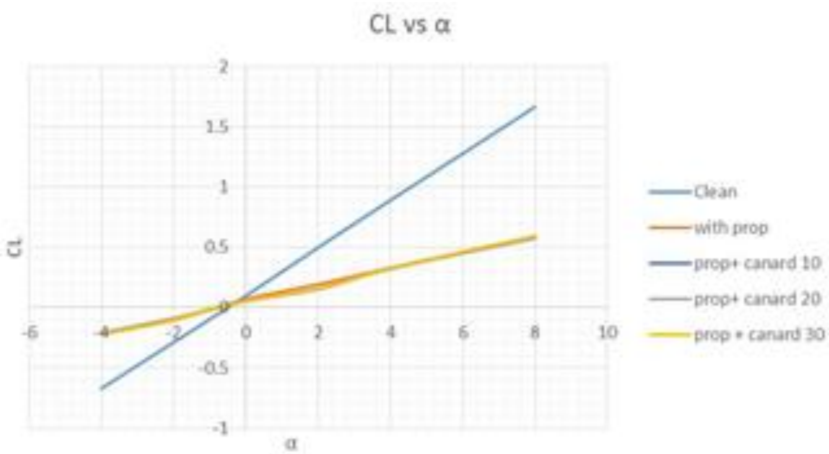

Fig. 4.3.1.1. Lift coefficient vs angle of attack comparison graph

4.3.2. Drag Coefficient

Comparison of drag coefficients between clean wing, wing with propeller and additional canards in new configuration with different span configurations is shown Fig. 4.3.2.1. The addition of propeller to the clean wing increase drag coefficient with increasing angles of attack. The effect of canard with longer span yields lower drag coefficient at low to moderate angles of attack compared to the wing with propeller configuration, but increasing along with longer canard span.

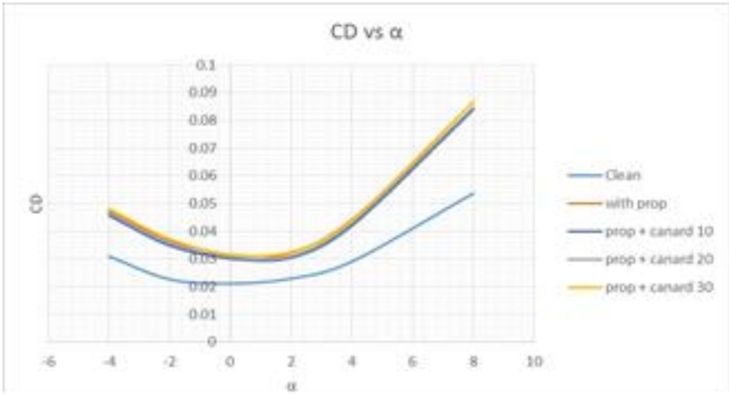

Fig. 4.3.2.1. Drag coefficient vs angle of attack comparison graph

4.3.3. Pitching Moment Coefficient

Fig. 4.3.3.1. shows comparison of pitching moment coefficients between clean wing, wing with propeller and additional canards in new configuration with different spans. From the result obtained, we can see that canard addition in new configuration gives negative slope which increase along with increasing span. We can conclude that the use of canard in new configuration can increase the stability of HALE UAV and creating a stable HALE UAV. The values of slope of pitching moment is shown in Table 4.3.3.1.

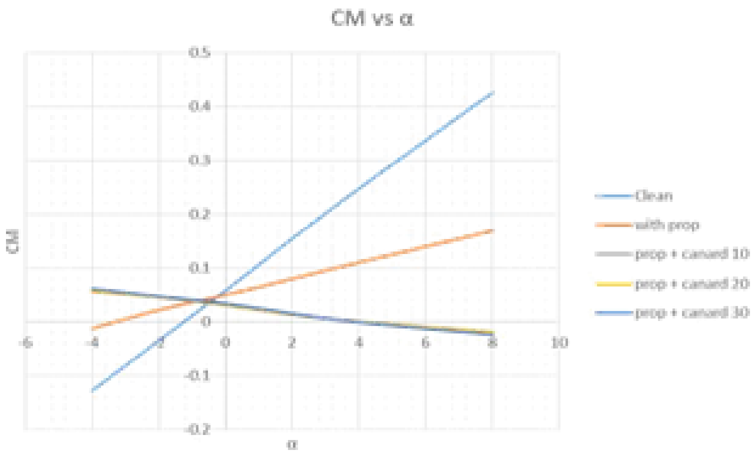

Fig. 4.3.3.1. Pitching moment coefficient vs angle of attack comparison graph

Table 4.3.3.1. Comparison of slope of pitching moments

Configuration	$C_{M\alpha}$(1/deg)
Wing only	0.0463
No Canard	0.0151
Canard 10 cm	-0.0062
Canard 20 cm	-0.0065
Canard 30 cm	-0.0071

4.4. Wing and propeller with different canard position

4.4.1. Variation in vertical position

Besides the variation of canard size, it is studied the effect of canard position, namely upper position (shifting 10 cm upward), in-line position and lower position (shifting 10 cm downward) with respect to to the propeller axis at zero degree angle of attack. The results of effect of various vertical position of canard is given in Table 4.4.1.1. The higher and lower position of the canard yields increased lift and drag and decreased pitching moment Generally, it is better to put the canard upward or downward the wing rather than in the same line with the wing, but we must consider the best trade-off between lift and drag.

Table 4.4.1.1 . Effect of variation in vertical position of canard

	Y = 0	Y = +10 cm	Y = -10 cm
Lift (N)	5.25	5.94	6.01
Drag (N)	3.01	3.03	3.07
Moment (Nm)	1.95	1.88	1.83
CL	0.0553	0.0626	0.0633
CD	0.0317	0.0319	0.0323
CM	0.0342	0.0330	0.0321

4.4.2. Variation in horizontal position

The change of canard position in horizontal direction is performed by maintaing the same distance between the propeller and wing traileing edge and varying the distance between canard and wing nose namely 5 cm backward, basis position, 10 cm and 20 cm forward from basic positions. The effect of canard shifting in horizontal direction is given in Table 4.4.2.1. The canard position shifting more forward gives increased lift and drag and decreased pitching moment. Therefore, it is better to put the canard more forward the wing but it must be take attention with the amount of pitching moment.

Table 4.4.2.1. Effect of variation in horizontal position of canard

	Basic Position	Forward 10 cm	Forward 20 cm	Backward 5 cm
Lift (N)	5.25	5.47	5.98	4.95
Drag (N)	3.01	3.04	3.1	3.03
Moment (Nm)	1.95	1.99	2.04	1.89
CL	0.0553	0.0576	0.0630	0.0521
CD	0.0317	0.0320	0.0327	0.0319
CM	0.0342	0.0349	0.0358	0.0332

5. Conclusion

The use of canard can give better longitudinal static stability of the HALE UAV with a requirement that its center of gravity lies in front of the aerodynamic center. Increasing the canard size yields higher lift and lower drag and increase longitudital stability. The results of the effect of change the position of canard can be concluded:

- it is better to put the canard upward or downward the wing rather than in the same line with the wing, but we must consider the trade-off between drag and lift.
- it is better to put the canard more forward the wing but it must be take careful attention with the amount of pitching moment addition.

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