# EXPERIMENTAL INVESTIGATION OF A BI-PLANE MICRO AIR VEHICLE

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## Abstract

*The focus of the paper is on the experimental investigation of a biplane micro air vehicle. The effects of various geometric parameters like gap, stagger and Decalage angle are investigated at low Reynolds number (~0.15 Million) in low-speed wind tunnel. Rigid-flat plate of aspect ratio one is used to evaluate all three geometric parameters. The maximum dimension of the single flat-plate is 0.15 m. The goal is to increase the aerodynamic performance of the biplane MAV by generating high lift and fly as slow as possible to capture high quality visual recordings. This will directly help to fly at a lower velocity and make tighter turns that are of advantage in restricted and narrow environment. Results show that the aerodynamic performance of the biplane MAV is significantly enhanced through the combination of gap and stagger effects. The optimal configuration of the biplane MAV is selected for further flight performance comparison with monoplane configuration.*

## 1 Introduction

The concept of biplane configuration can be traced back to early days of aviation. The revolutionary powered flight at Kitty Hawk, North Carolina, on December 17, 1903 was also a biplane configuration. General biplane theory was extensively documented in early 1920's and is commonly known as Munk [1] theory. Several experimental studies [2-4] were conducted in 1920's to evaluate the effect of various geometric configurations. However, the subsequent developments of structural and aero-elastic sciences resulted in abandoning the biplanes over high aspect ratio configurations.

Recently, there is an increasing interest in the development of Micro Air Vehicle (MAV) as an inexpensive and expendable alternative for mission where larger Unmanned Air Vehicles (UAVs) are difficult to operate. The typical flight scenarios such as close-field battle support, post-attack near-area surveillance, narrow space environments like caves and tunnels can only be accomplished by MAVs. It should be noted that the MAVs are strictly defined by their dimensional size and therefore, high aspect ratio configurations are definitely not the solution. The advantages of biplane configuration in terms aerodynamic efficiency for dimensionally constrained configurations are well known.

One of the problems found of fixed-wing MAVs is the difficulty in capturing high quality visual data during flight. This is because the monoplane MAVs are required to fly at relatively high speed in order to produce significant lift from its limited wing area. This compromises the quality of data captured and reduces its effectiveness during missions. A possible alternative to circumvent this problem is to design a biplanar configuration. Biplane MAV can increase the aerodynamic performance of the MAV by contributing the desired lift at significantly low speed to monoplane MAV.

The study of biplane configurations as a potential platform for MAV applications has been recently studied by several technological protagonists. It should be noted that the MAV flight envelope falls in low Reynolds number regime that poses another problem. The sensitivity of aerodynamic data increases significantly at low Reynolds number, therefore, the general biplane theory needs to be revisited.

Traub [5] has studied the possibility of biplane delta wing configuration as a potential aerodynamically superior platform for MAV applications. The experimental investigations are carried out on 75-deg delta wings. Effect of gap and stagger are evaluated. A theoretical model is developed by combining Prandtl lifting theory and Polhamus [6] leading edge suction analogy. The effects of gap between two wings are more pronounced than stagger. Moreover, the theoretical model is validated with the experimental data. However, the applicability of the theoretical model to other planform shapes such as rectangular, elliptical or Zimmerman is yet to be seen.

Moschetta and Thipyopas [7] have compared the performance of monoplane MAV over a biplane configuration. The study encompasses the optimization of geometric variables (stagger, gap, Decalage angle and aspect ratio) through numerical investigations and wind-tunnel validations. Moreover, the propeller interaction with the biplane configuration is also studied. The results show the promising potential for biplane MAVs as an alternative to monoplane platforms.

In this paper, wind tunnel testing of both monoplane and biplane configurations is discussed. First, a generic wind-tunnel model is fabricated to vary the geometric parameters like gap, stagger and Decalage angle. Then the experimental data is collected at low Reynolds number in low speed wind-tunnel. Rigid flat-plate rectangular wings of aspect ratio 1 are used to evaluate all three identified geometric parameters. The best lift-to-drag ratio optimal configuration of the biplane MAV is selected and is further used for the analysis. The analysis entails comparison between monoplane and optimized biplane flight performance parameters. The results indicate that gap and stagger effects govern aerodynamic performance more dominantly than Decalage angle. Finally, the flight performance comparison is carried out between monoplane and optimized biplane configuration.

## 2 Experimental Setup

### 2.1 Model Description

In order to evaluate the aerodynamic performance of the biplane MAV, a wind-tunnel model is fabricated. The key features of the bi-planar prototype are the ability to adjust the three geometric parameters, gap, stagger and Decalage angle. Gap is defined as the vertical distance between the two wings. Stagger is the relative horizontal position of the leading edge of upper wing and the leading edge of lower wing, with positive defined as leading edge of upper wing is in front of the of leading edge of lower wing and vice versa. Decalage angle is the angle of upper wing with respect to the horizontal plane of the lower wing as shown in Fig. 1.

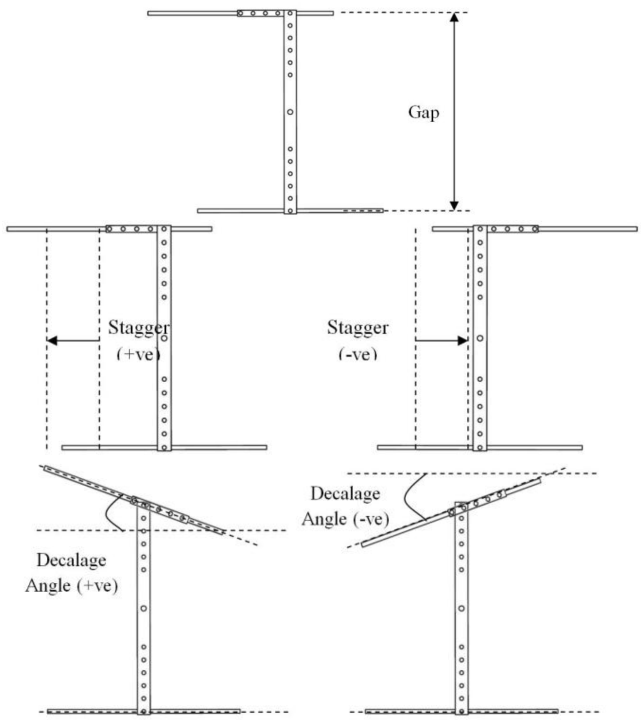


Fig. 1 Geometric attributes: Gap, Stagger and Decalage angle

The design of the prototype is extremely important as it will affect the accuracy of the wind tunnel measurements and it must have structural integrity to be able to withstand the aerodynamic loads. The wings are designed according to the dimensional restriction imposed to a typical MAV. The wings are of aspect ratio equal to 1.00, thickness-to-chord (t/c) ratio of 2.67% and chord-length of 0.15 m. the edges of the rectangular plates are filleted with 0.01 m radius circles. The struts are manufactured using aluminum plates with various screw holes drilled onto it. They are covered with masking tape during experiment to avoid any flow disturbances. The gap, stagger and Decalage angles can be easily altered by fixing the wings onto the respective holes and tightened using bolts and nuts. An arc rod is used in addition to further secure the wings when the Decalage angle between the wings is altered. Fig. 2 shows the final prototype with wings mounted on the frame inside the wind-tunnel facility.

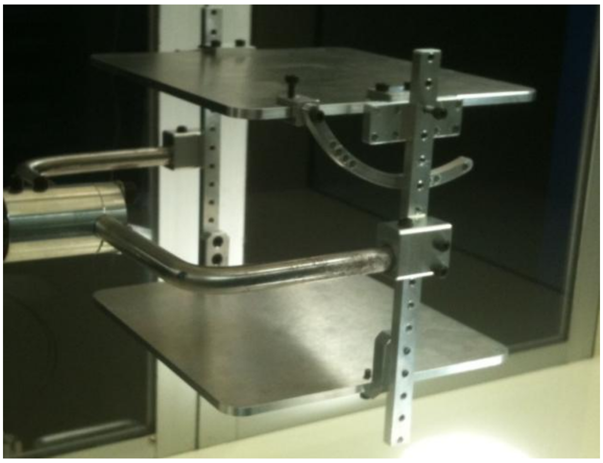

Fig. 2 Final Biplane assembly with wings installed

## 2.2 Wind Tunnel Facility

The Nanyang Technological University (NTU) low speed, low turbulence closed loop wind-tunnel facility is used to test the full scale bi-planar prototype at various geometric configurations. The dimensions of the internal surfaces of test-section are 0.72x0.78x2.00 m. A six component sting balance is used to measure all forces and moments. The model positioning system is of quadrant type and is equipped with a sting model support. It is capable of allowing the model to perform rotations in three axes, namely roll, pitch and yaw. The data acquisition system is based on National Instruments (NI) platform and Lab-View based software to graphically view and record the data. It is known as Data Acquisition, Reduction and Control System (DARCS). The wind-tunnel test section is shown in Fig. 3.

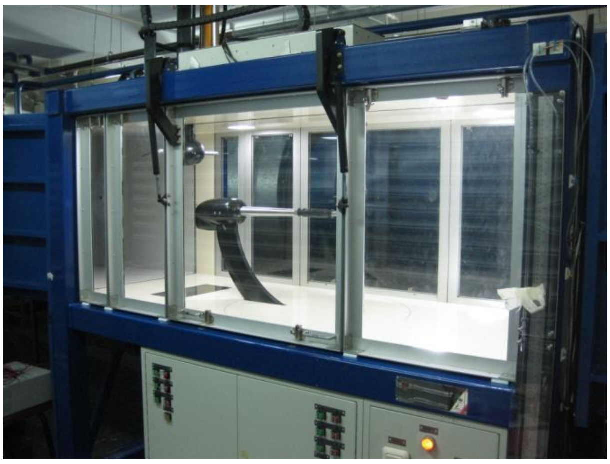

Fig. 3 Closed-circuit wind-tunnel test section with sting balance

# 3 Parametric Studies

## 3.1 Monoplane vs. Biplane

In this section, the lift performance of the monoplane against the biplane configuration for various gaps is considered. The motivation for adopting the biplane configuration is due to the increase in its lift. It is evident in Fig. 4 that the magnitude of lift produced by monoplane is significantly less than biplane configurations. For the gap of $0.533\bar{c}$, an increase in lift at low angles of attack ($\alpha \leq 10^{o}$) is observed to be between 64%-158%, whereas at high angles of attack ($\alpha > 10^{o}$), the increment is between 30%-66%, as compared to the monoplane. For the gap of $1.067\bar{c}$, the ranges of lift increment are 115%-225% for low $\alpha$ and $65\% - 95\%$ for high $\alpha$ which is double than $0.533\bar{c}$ case.

However, the coefficient of lift for monoplane configurations will be higher because the area required to non-dimensionalize the biplane MAV is twice of monoplane. Moreover, as the gap between biplane configurations is decreased, strong interference between the two wings result in the degeneration of the lift that is an undesired situation. The detailed analysis of effect of gap is done ahead.

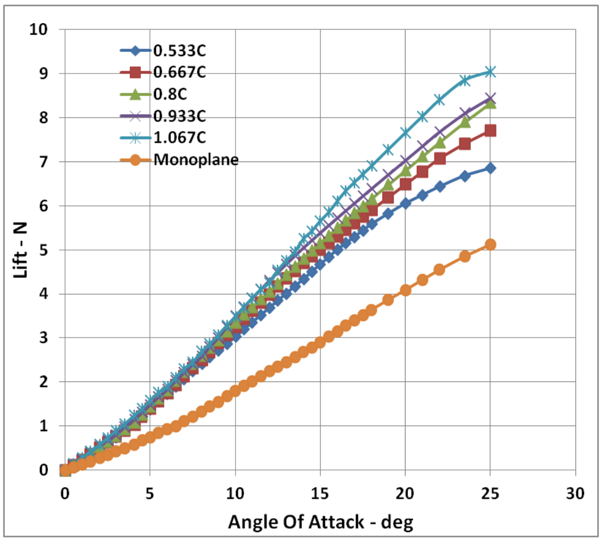


Fig. 4 Lift of monoplane and biplanes (various gaps)

## 3.2 Effect of Stagger

The effect of stagger is evaluated at zero Decalage angle and two gap positions, $0.533\bar{c}$ and $1.067\bar{c}$. The coefficient of lift at the gap position of $0.533\bar{c}$ is shown in Fig. 5. It can be seen that as stagger increases from negative to positive, $C_{L_{\max}}$ and $C_{L_\alpha}$ increases. This is due to the interaction between downwash and upwash of upper and lower wing respectively. The close proximity of the upper wing helps to re-energize the air flow over the upper surface of the lower wing, thus delaying the onset of flow separation, resulting in an increment in lift. As stagger become more positive, the upwash of lower wing will be influenced by upper wing more dominantly, thus delaying the onset of flow separation. This will result in the increment in lift. The increase in $C_{L_{\max}}$ is approximated up to 16% as reflected in Fig. 5.

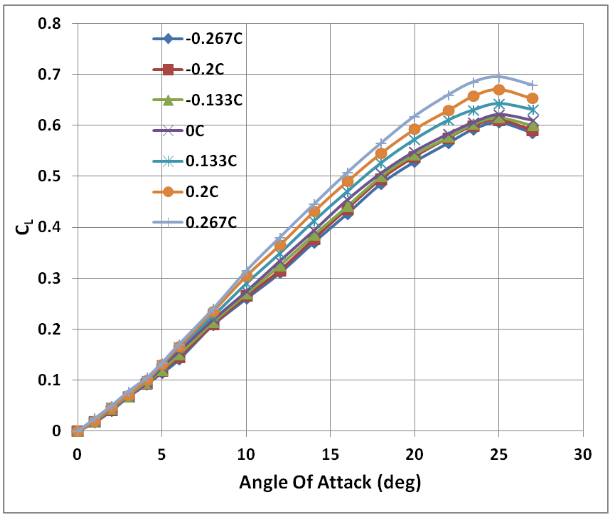


Fig. 5 Effect of Stagger on Lift at $0.533\bar{c}$

On the other hand, when the gap is increased from $0.533\bar{c}$ to $1.067\bar{c}$, the overall coefficient of lift is improved with the increase in gap. However, the flow interaction between the two wings is significantly reduced thereby lift variation become insensitive to stagger effect as shown in Fig. 6. Therefore, it can be concluded that the effect of stagger on $C_{L_{\max}}$ and $C_{L_\alpha}$ is only significant for low gap configurations.

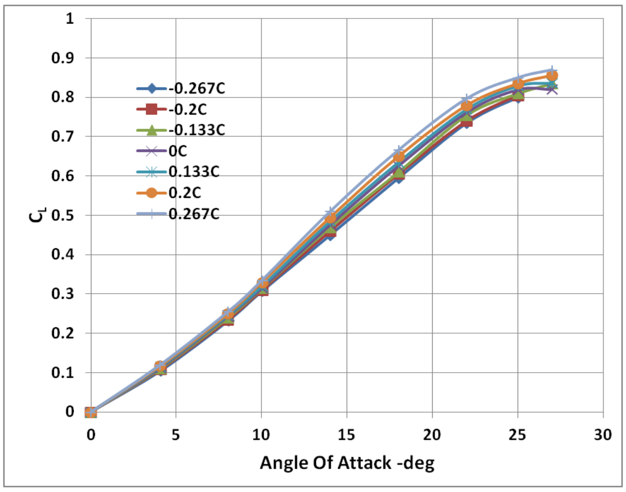


Fig. 6 Effect of Stagger on Lift at $1.067\bar{c}$

## 3.3 Effect of Decalage Angle

The effect of Decalage angle on coefficient of lift is evaluated at zero stagger and two gap positions, $0.533\bar{c}$ and $1.067\bar{c}$ as shown in Fig. 7 and Fig. 8.

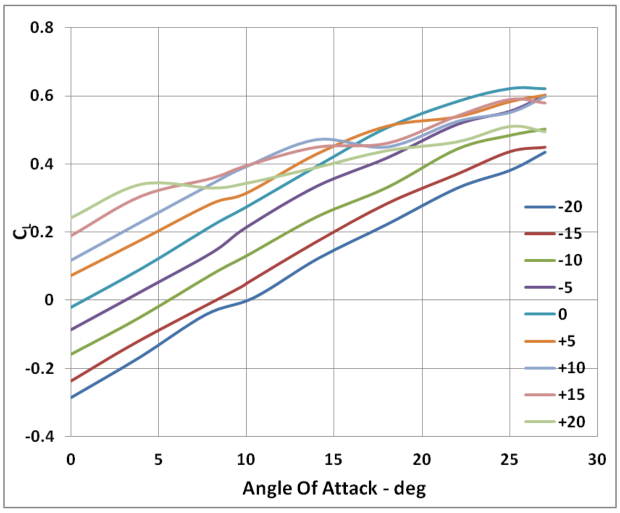


Fig. 7 Effect of Decalage Angle at 0.533C gap and zero stagger

It is evident that the coefficient of lift increases consistently with the increase in Decalage angle. However, the lift behavior is subtle. The increment in lift with the positive Decalage angle comes primarily from the geometric angle of attack change from upper wing. Therefore, once the Decalage angle is negative, a decrement in lift is observed.

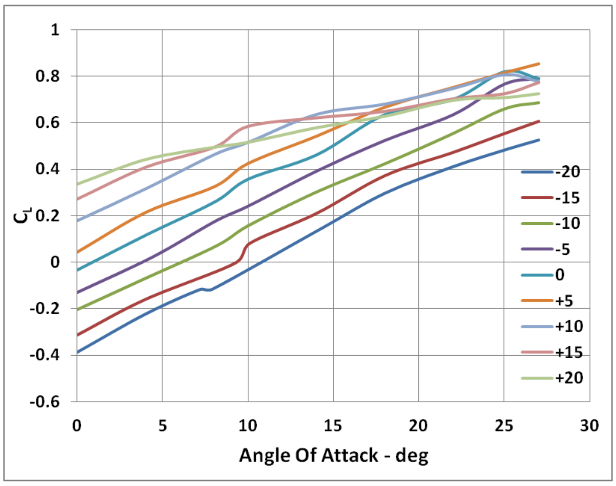


Fig. 8 Effect of Decalage angle at 1.067C gap and zero stagger

The stall behavior is also decoupled with Decalage angle variation. It can be seen in Fig. 9 that two bumps are present in the typical lift graph. The Decalage angle is $20^{o}$ in the present case. The first bump is due to the stall of upper wing whereas the second bump is from the lower wing. However, it is observed that there are no evident advantages of Decalage angle in the optimal configuration.

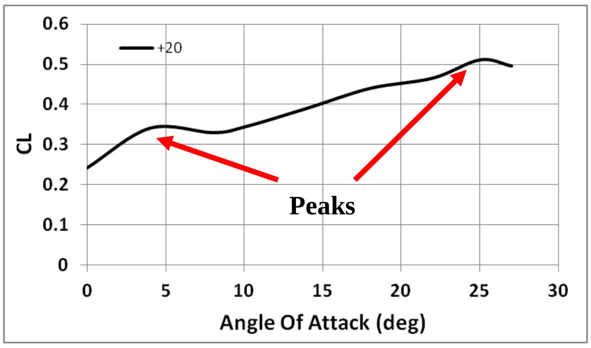


Fig. 9 Emergence of two peaks at 0.533C gap, zero stagger and 20 deg Decalage angle

## 3.4 Effect of Gap

The gap between the two wings governs the major contribution of aerodynamic effects. The coefficient of lift for various gap configurations against angle of attack is shown in Fig. 10. For reference purpose, coefficient of lift of monoplane is also plotted. The gap distance between two wings is non-dimensionalized with the chord-length. It can be observed that the lift coefficient of monoplane is larger than the biplane wings. However, as the gap between the two wings is increased, the lift at high angles of attack approaches monoplane case. This is the clear indication that the vortex induced lift for biplane configurations is lesser than monoplane counterpart.

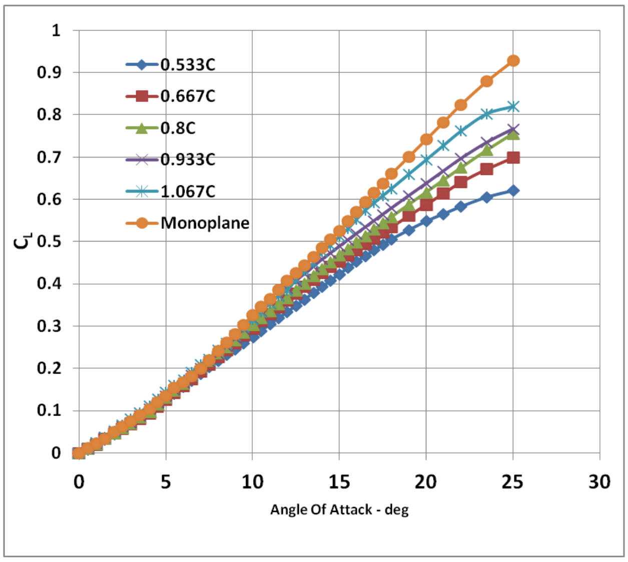


Fig. 10 Coefficient of Lift for various gap positions

It is evident that there is an increase in the lift curve slope, as gap increases. Moreover, the maximum lift coefficient also increases with gap, up to 32% at $1.067\bar{c}$ . This is mainly due to the diminishing effect of flow interference between the two wings. The stall angle hovers around 25o for all values of gap. This reflects the independency between the stall angle and gap.

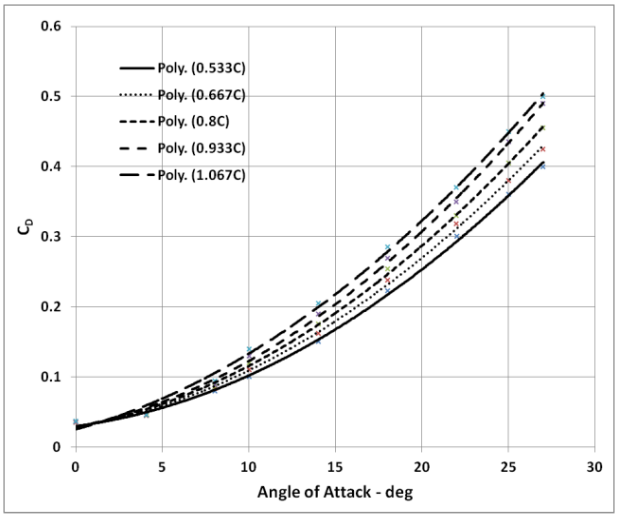


Fig. 11 Coefficient of Drag for various gap positions

The effect of gap on coefficient of drag is shown in Fig. 11. It is evident that the drag increases with the gap. The vortex lift contribution increases with the gap thereby increasing the drag coefficient. At low angles of attack, the increment in drag is less than 5% overall. However, as the angle of attack increases, the drag profile becomes more separated across various gaps. An increase in drag of up to 25% is observed at 25$^{o}$ angle of attack. This implies that the majority of the drag contribution comes from induced drag.

The effect of gap on coefficient of pitching moment is shown in Fig. 12. The pitching moment shown is calculated at the leading edge of the bottom wing. The static stability $C_{M_\alpha}$ should be negative for stable configuration. All configurations show stable behavior. Moreover, the stability increases with the increase in gap. The $C_{M_o}$ is positive for all gap configurations implying that all configurations are trim-able. Therefore, the stability of the biplane configuration can be adjusted without compromising the trimmed $C_M$ of four to five degrees.

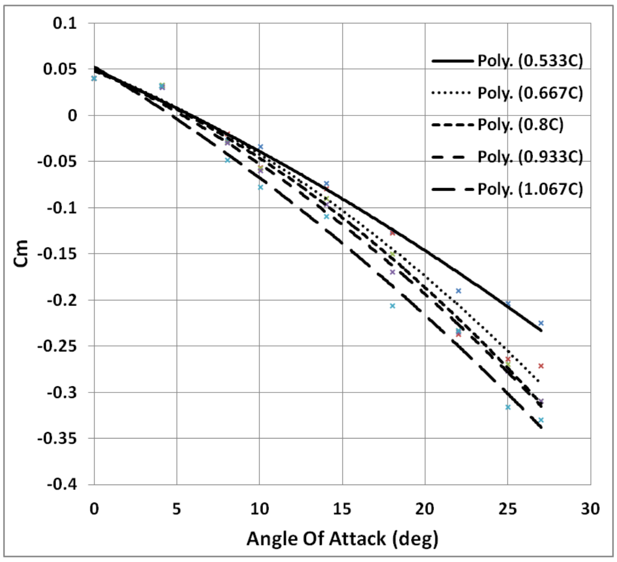


Fig. 12 Coefficient of pitching moment for various gap positions

## 3.5 Final Optimized Biplane Configuration

Through the study of the geometric effects on the aerodynamic performance of a bi-planar MAV, it is possible to identify the possible biplane configurations that will optimize the MAV based on the requirement of its mission profile. The optimization process should be conducted separately for MAV with different missions as the criteria identified might not be the right parameter to optimize other flight parameters. During this study, the optimized biplane configuration is selected based on highest lift-to-drag ratio (L/D). In order to obtain higher L/D, corresponding increase in lift and decrease in drag must be achieved. Based on experimental data, a biplane configuration of positive stagger and low gap should be able to achieve highest L/D. The optimal configuration selected is for $0.533\bar{c}$ gap, $0.267\bar{c}$ stagger and zero degree Decalage angle.

# 4 Flight Performance Study

The flight performance comparison of both monoplane and optimized biplane configuration is discussed in this section. The configuration used for monoplane is identical to the wing used for the wind tunnel testing – chord length 0.15 m, aspect ratio of 1 and thickness-to-chord ratio of 2.67% whereas for biplane, the selected configuration is the one as discussed in Section 3.5 above. The weight component analysis of both configurations flying prototype is based on Black Widow MAV [8]. The rationale behind using the same mass breakdown to our performance analysis is based on geometric similarity. It has a similar wing span as the wing used in the wind-tunnel testing. It is designed to fly at 13.4 m/s, with an endurance of 30 min and a maximum flight range of 2 km. The overall mass distribution of the Black Widow MAV is shown in Fig. 13.

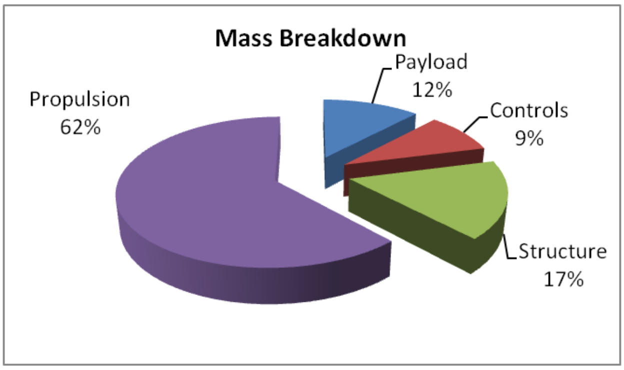


Fig. 13 Mass Breakdown of Black Widow MAV

The weight of the monoplane is approximated using the Black Widow MAV. The weight of the biplane configuration is calculated by adding the structural weight of an additional wing to the overall configuration. The values of $C_{L_{\max}}$, $C_{D_o}$ and $k$ are calculated using the aerodynamic data from the wind-tunnel experimentation. The respective data of monoplane and biplane configurations are shown in Table 1.

Table 1 Monoplane and biplane aerodynamic performance parameters

| **Configuration** | **Monoplane** | **Biplane** |
|---|---|---|
| $C_{L,max}$ | 1.250 | 0.695 |
| $L/D_{max}$ | 2.306 | 3.440 |
| W | 0.0565 | 0.0661 |
| S | 0.0225 | 0.0450 |
| $C_{D0}$ | 0.031 | 0.0263 |
| k | 9.539 | 2.555 |

The level flight performance is tabulated during the cruise velocity of 20 m/s and air density of 1.225 kg/m$^3$. The minimum power required is calculated through Eq. (1).

$$P_{R,min} = \left(\frac{2W^3}{\rho_\infty S}\left(\frac{C_D{}^2}{C_L^3}\right)_{min}\right)^{\frac{1}{2}} \tag{1}$$

The velocity at minimum power required:

$$V_{(P_R)min} = \left(\frac{2}{\rho_\infty}\frac{W}{S}\sqrt{\frac{k}{3C_{D_0}}}\right)^{\frac{1}{2}} \tag{2}$$

The stall speed is given by:

$$V_{stall} = \sqrt{\frac{2}{\rho_\infty}\frac{W}{S}\frac{1}{C_{L_{max}}}} \tag{3}$$

The power available depends on the energy source used in the MAV. Generally, batteries are used in MAV due to its lower energy usage. The choice of batteries usually depends on the aerodynamics performance of the MAV. In this case, to provide a clearer picture, the power available for both configurations will be fixed at 4 Watt. For a steady and un-accelerated climb of a propeller driven MAV, the maximum rate of climb is given by:

$$(R/C)_{max} = \frac{P_A}{W} - \left[\frac{2}{\rho_\infty}\sqrt{\frac{k}{3C_{D_0}}}\left(\frac{W}{S}\right)\right]^{1/2}\frac{1.155}{(L/D)_{max}} \tag{4}$$

Its corresponding velocity is given by:

$$V_{(R/C)max} = \left(\frac{2}{\rho_\infty}\frac{W}{S}\sqrt{\frac{k}{3C_{D_0}}}\right)^{1/2} \tag{5}$$

For a steady, unaccelerated descent, the small equilibrium glide angle is given by:

$$\tan(\gamma_g)_{min} = \frac{1}{(L/D)_{max}} \tag{6}$$

Its corresponding velocity is given by:

$$V_{R_{max}} = V_{(L/D)max} = \left(\frac{2}{\rho_\infty}\frac{W}{S}\sqrt{\frac{k}{C_{D_0}}}\right)^{1/2} \tag{7}$$

The maneuvering performance comparison between monoplane and biplane is also carried out. For level turn:

$$R_{min} = \frac{4K(W/S)}{g\rho_\infty(T/W)\sqrt{1-4kC_{D,0}/(T/W)^2}} \tag{8}$$

The corresponding velocity for the level turn can be estimated by:

$$(V_\infty)_{R,min} = \sqrt{\frac{4k(\frac{W}{S})}{\rho_\infty(\frac{T}{W})}} \tag{9}$$

The load factor during the level turn is approximated as:

$$n_{R,min} = \sqrt{2 - \frac{4kC_{D,0}}{(\frac{T}{W})^2}} \tag{10}$$

The endurance is calculated from the following relationship:

$$E = \frac{n.\varepsilon_A}{P_R} \tag{11}$$

Given both configurations used the same propulsion system, and using the battery source of the Black Widow as a guide,

$$n = 0.8\ (assumed)$$
$$\equiv\ \approx\ 8400\,J$$

Since MAVs are powered by batteries, there range is typically independent of weight variation and is calculated as follows:

$$R_g = \int_0^E V_g\, d_t \tag{12}$$

The flight performance parameters are computed based on Eq. (1) to Eq. (12) and shown in Table 2 below.

Table 2 Summary of flight performance parameters

| **Flight Parameters** | **Monoplane** | **Biplane** |
|---|---|---|
| *Cruising* | | |
| Min. Power Req. (Watt) | 0.518 | **0.146** |
| Vel.@Min.Pwr.Req. (m/s) | 5.690 | **3.694** |
| Stall Speed (m/s) | 1.81 | 1.85 |
| *Climbing* | | |
| $ROC_{max}$ (m/s) | **66.769** | 58.369 |
| Vel. @ $ROC_{max}$ (m/s) | 5.690 | **3.694** |
| *Gliding* | | |
| Glide Angle (rad) | 0.409 | **0.283** |
| Glide Vel. (m/s) | 7.488 | **4.862** |
| *Manoeuvring* | | |
| Min. Radius (m) | 2.002 | **0.386** |
| Vel. @ Min. Radius (m/s) | 3.926 | **2.895** |
| *n* @ Min. Radius | **1.387** | 2.428 |
| *Endurance and Range* | | |
| Endurance (min) | 19.52 | 19.25 |
| Range (m) | 23440 | 23095 |

For the cruise mission segment, biplane has dominated monoplane MAV in terms of minimum power required and reduced velocity. This has been achieved by the significant increment in lift. Moreover, the reduced flight velocity is the main objective to capture and transmit high quality visual data from cheap cameras at low frame rate.

The improvement in glide performance is also significant especially in terms of velocity and glide slope angle. This will ensure the ground operator for easy and smooth recovery of the MAV during landing. During level turn, the improvement in performance of biplane MAV in terms of minimum radius of turn up to 80% but at the cost of increment in load factor. The endurance and range performance are not significantly affected from the biplane configuration. However, the rate of climb for biplane MAV is reduced but the difference is not significant. Therefore, the climb performance can be traded off over cruise, glide and level turn performance.

## 5 Conclusion and Future Work

The paper entails the experimental investigation of a bi-planar MAV through wind-tunnel testing. The objective was to study the effect of three parameters – Gap, Stagger and Decalage angle. It is found that gap plays a vital role in determining the degree of flow interference occurring between the wings. Results show that the aerodynamic performance of the biplanar MAV will be enhanced through the proper combination of gap and stagger adjustments.

From flight performance analysis, biplane helps little in the improvement in endurance and range, however, the payload capacity and maneuvering in tight spaces is significantly improved.

As gap plays a dominant role in biplane studies, future work will study the effect of gap for different aspect ratios and planform shapes. Moreover, some theoretical aerodynamic estimation formulation will be developed around that as well.

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