Analysis of Folding Wing Rolling Moment

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ABSTRACT

Mini and micro aircraft are required to be a multi functioning; which can both maneuver in forward flight and hover for takeoff configuration. This leads to the development of the folding wing aircraft. The folding wing cannot apply any control surface to create a rolling movement because it must move all the time. The benefit of folding is an idea for rolling moment generation. This is an asymmetrical lift that generates form folding unequal area between left and right wing. Therefore, this research focuses on finding a relationship between rolling moment generated by the asymmetrical force and the area ratio of two wings by using CFD simulation to predict them. Firstly, the design of the wing is simulated in cruise condition at various angles of attack to determine the trim angle and the significant aircraft characteristics. Then the trim angle was set at the condition for computing the rolling moment for 3 levels of wing folding. The three levels are not too different in overall wing area, but the area of the two sides are imbalanced so that can generate different rolling moment. The result of the simulation shows that the asymmetry of the wings can generate a rolling moment and it increases dramatically when the area ratio rises.

1 INTRODUCTION

Generally, there are three control axes on the aircraft that are longitudinal, lateral and vertical axis that are called roll, pitch and yaw respectively. Nowadays, the mini and micro aircraft developers desire the multi-mission aircraft that can do a various task [1, 2]. That is the reason to develop the wing that can fold. It is easy to transport and that can also achieve a high performance vertical takeoff because of less drag from the big wing area when hovering. According to the folding condition, the conventional rolling control surface; aileron, on the normal fixed wing is difficult to install. This is a challenge to research and develop a new process to control rolling motion. The object of this research is to determine the relation between different of the wing area when folded and the rolling moment that is generated by using Computational Fluid Dynamics (CFD) to find all of the aircraft parameters and compare them to the original fixed wing which was named Brown that are designed for multi-missions that can maneuver in forward flight and hovering in takeoff configuration. The developed folding wing must replace the original in the same or better performance. There are many ways to roll the aircraft but the principle of rolling control is to generate asymmetric lift between two wings. For example, Bamber [1934] [3] created some new components called Floating Wing Tip Aileron which is installed at the end of the wings to make a rolling moment to escape a stall situation, Next Rao [1983] [4] attached an additional control surface to the leading edge. When it works, the position of lift force acting on each side is changed and counteracts any instability. In the progression of material science in the 21st century, Raney [2000] [5] makes an effort to use the smart material to make the flexible wing for adapt its shape to be the suitable shape of rolling motion. Furthermore, Ifju [2005] [6] claimed that there are a plenty of benefits from the wing which can flex same as to the natural way. The result of wind tunnel experiment and CFD are the same trend that shows the flexibility provides for smoother flight than conventional wings. They do not have only good maneuverability and also can delay stall. It can be seen that the method attempted was to follow a natural way like how birds can flex their wings. The simulation of the computation of fluid mechanics was to set the flow as laminar flow and increase the number of elements. This method tries to avoid using turbulence flow which makes the calculation more difficult.

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2 METHOLOGY

This analysis was divided into 4 parts. First of all, the complex wing was simplified to be a thin plate that is 2 mm thick but the platform is similar to the original. Secondly, there is a determination of grid independence in the Flow Simulation Program by increasing the number of elements within the model. Then, the simplified wing was simulated in the program to calculate the aircraft characteristics of the wing. Eventually, the computational process of simplified folded wings was simulated to find the moment coefficient when the wing was folded. However, there are some information about aircraft and setting the simulation program.

2.1 *Aircraft specification and other parameters*

Some significant parameters and aircraft performance of the original aircraft (Brown) were assigned by the developer as shown in table 1. This new folding wing must follow the maximum take of weight (MTOW), lift coefficient and rolling coefficient. Wing platform was design from the shape of birds wing, so it is somewhat of strange platform. The wing diameter is shown in Fig.1.

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MTOW	Vcruise	S;m2	C;m	b;m	CL	Cl
0.5 kg	15 m/s	0.13	0.25	0.48	.274	.00349

Table 1: The aircraft parameters defined by the original aircraft.

2.2 *Analysis of the force and moment data*

The simulation model was set axis follow by the aircraft principal axis. They have 3 axes; longitudinal, lateral and vertical axis that are represented by letter X, Y and Z respectively. The direction of the axis is shown in Fig.1 and its origin is assumed at the center of gravity of the wing. Moreover, this point position and the axis in another model is same as this wing.

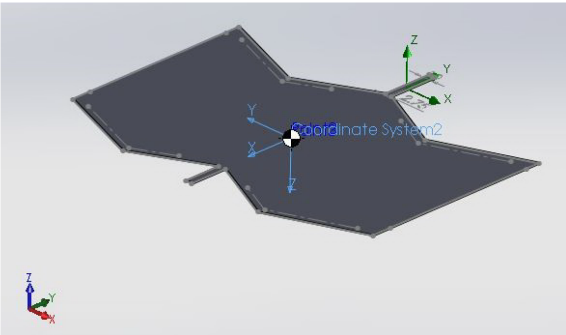

Figure 1: Setting axis for simulation.

If there is some angle of attack between wing and wind direction, lift is not the Z-direction force, which can read from simulation result, so it must be calculated by vector method. Lift and drag force are shown in Fig.2 which are the composition of the X and Z force.

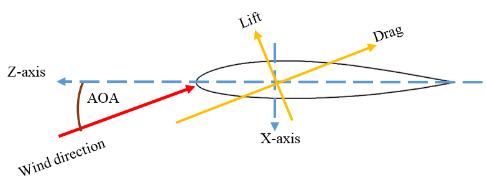

Figure 2: Aircraft axis and aerodynamic force axis.

2.3 *Simplified wings*

The actual folding wing has a lot of components such as bolts, nuts, wing axis and plates. If the simulation takes all of the wing components into account, it will be waste of resource and also too complicated to compute. Thus, the wing that have a plenty of plates was simplified to be normal wing that is a thin plate in the original wing planform. The simplified wing in cruise condition is shows Fig.3.

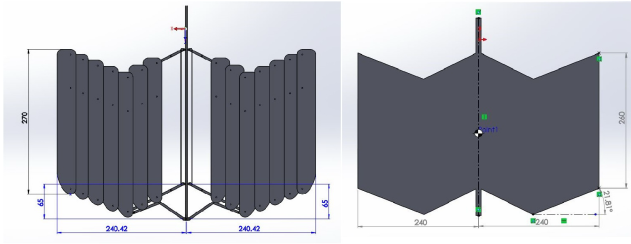

Figure 3: Comparison between actual (left) and simplified (right) plain wing.

2.4 *Domain dependence*

Domain is the region where the simulated pass. The domain size is one of the factor that tell how fast the analysis. If this is an enormous domain size, there is waste of time. Following this, the suitable domain size should be calculated. First of all, the full domain size 8 times of chord that 4 m wide along left to right, 2 m long in back, 1 m in front and 2 m high was set as the first trial domain size. Secondary, there is an idea to make the domain to be symmetry because it may reduce calculation time. This lead to symmetry domain that use the size 8 times same as the first one, but it computes only left wing. This usage time is haft of the first domain. Then, the bigger domain was set to check the flow behavior. This was defined as 20 times of chord. The result of this calculation is not noticeably difference from the previous calculation. The lift coefficient of each domain and show in table **??** the error in this table compare with the original required lift coefficient ,0.274. Overall, the 8-time-chord domain dimension was chosen to the next step simulation because the error of lift coefficient is under 5 percentage and the usage time is minimal.

Domain	Lift coef.	Drag coef.	error
(2+2)x(2+1)x(1+1)	0.2764	0.0385	0.90
(2+0)x(2+1)x(1+1)	0.2876	0.0394	4.99
(5+0)x(5+2.5)x(2.5+2.5)	0.2789	0.0387	1.80

Table 2: Result in lift coefficient for different domain sizes. Domain:(left+right)x(back+fornt)x(top+bottom)

2.5 *Set up simulation model for plain wing*

For the plain wing analysis, the wing is symmetrical, so it can be computed only half wing by using the symmetrical domain to reduce the number of element. The domain dimension (in section 2.4) is 3 m long (1 m front and 2 m back), 2 m wide with the symmetric half wing and 2 m height. Other flight conditions were assigned to the atmosphere and the wind velocity magnitude of 15 m/s and the direction was changed by the vector component method shown in Y and Z direction followed by the adjustment angle of attack.

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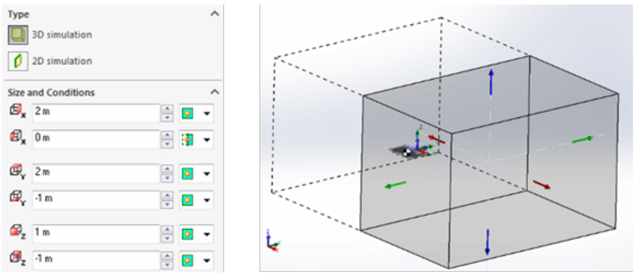

Figure 4: Computation domain.

2.6 *Grid dependence*

The original aircraft with fixed wing was designed for carry 0.5 kg total weight and the angle of attack at 6-degree cruise condition. Therefore, this condition is set to be the validation condition that grid is meshed fine enough to compute lift force equal to the carrying weight. Grid independence is the process to find the minimal element number that will give the best result. In addition, it can avoid to waste computer resource. Firstly, the model was meshed in the coarse level and simulate to measure the lift force to compare with the original plane condition, afterwards it was meshed in the finer level (coarse and fine mesh are shown in figure 5). Following that, lift coefficient for each mesh levels were calculated each mesh level and they were plot (figure 6) and find the different between the coarse and the finer. According to figure 6, the difference of lift coefficient between mesh level 3 which has 1362844 elements and mesh level 4 which has 2589254 elements accounts for 9.274percentage and the difference between mesh level 4 and 5 (4706688 elements) forms 4.780percentage. In addition, the difference value of level 5 and 6 (8228096) is 4.496. The last two figures show the small difference percentage (less than 5percentage), so the mesh level 5 that has element exceed 4700000 was chosen to be the simulation grid number.

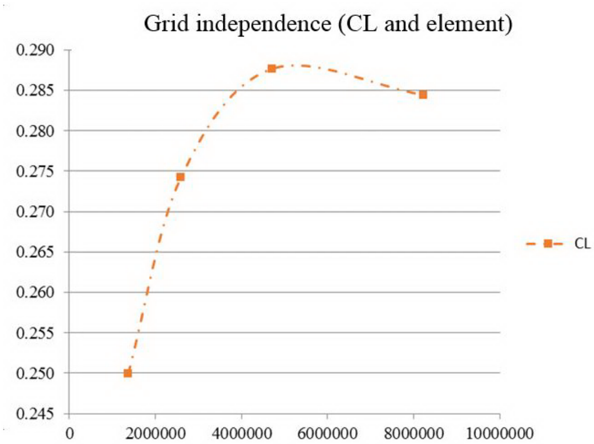

Figure 5: Grid independence.

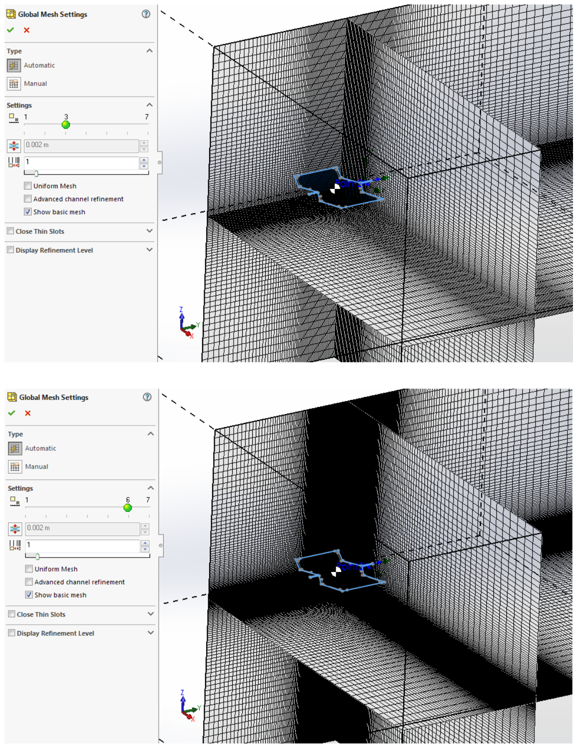

Figure 6: Compare mesh level between level 3 (left) and level 6 (right).

2.7 *Simulation of asymmetry wing*

The simplified folding wings were simulated in CFD program to compute rolling moment generated by asymmetry wing planform between two side. The wing was folded in 3 levels as shown in figure 7-9 respectively. The area of two side wing in each level were illustrated in table 3. Because of asymmetry of wing, they cannot be simulated by using symmetry domain to reduce the computer resources. Thereby, these three case of folding use full domain. The condition is, however, similar to the assigned condition for the plain wing such as the wind velocity of 15 m/s and 6-degree angle of attack.

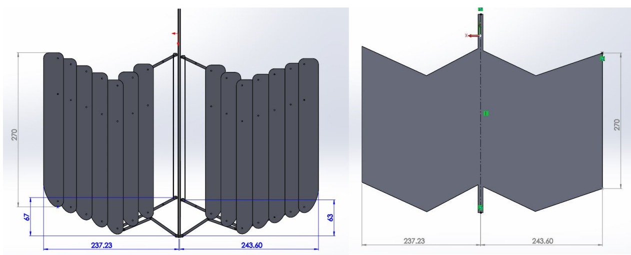

Figure 7: Folding wing level 1 (actual: left, simplified: right).

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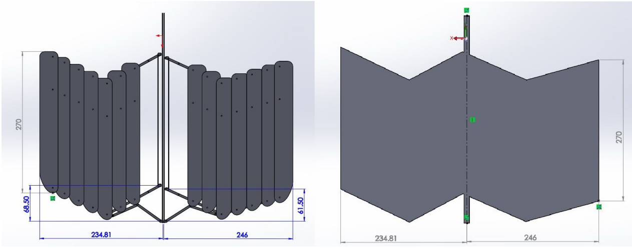

Figure 8: Folding wing level 2 (actual: left, simplified: right).

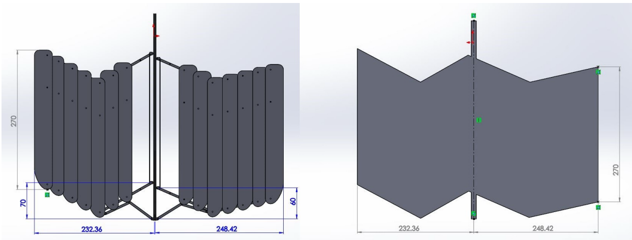

Figure 9: Folding wing level 3 (actual: left, simplified: right).

3 Results

3.1 *Aircraft characteristic for plain wing*

After set all of the condition in the simulation program and mesh the model at the chosen level, aircraft characteristics of the plain wing were determined by CFD approach to calculate all of the aerodynamic forces that acting on the wing at any angle of attack. This process is conducted to ensure the trim angle of attack of the wing and to find certain significant characteristics that will illustrate the stability and aerodynamic performance of this wing. Raw data collected from program result were transferred to aerodynamic force by their definition. Eventually, they were calculated to be their coefficients in the different angle of attack that was the characteristics of this wing as shown in table **??**. The characteristics is 2 groups. One is force coefficients including lift coefficient and drag coefficient, they represent by CL and CD. The other one is moment coefficient that calculate around center of gravity. They are pitching (Cm), rolling (Cl) and yawing (Cn) moment coefficient. There are graphs that

Parameters	Plain wing	Fold 1	Fold 2	Fold 3
Right span;m	.240	.237	.235	.232
Left span;m	.240	.244	.246	.248
Right pin;mm	65.00	67.00	68.50	70.00
Left pin;mm	65.00	63.00	61.50	60.00
Right area;m2	.06620	.06541	.06481	.06421
Left area;m2	.06620	.06699	.06758	.06817

Table 3: Lift coefficient at any mesh level and the different between two level.

plot between angle of attack and force coefficients in figure 10 and the moment coefficients in figure 11. Then, the lift curve slope was determined. This makes up approximately 0.057 1/deg. In addition, the trim angle was found when the lift force equal to weight that was 0.5 kg, so the trim angle of this wing is approximately 6 degrees in cruise condition. Lift over drag coefficient was calculated and plot in figure 12.

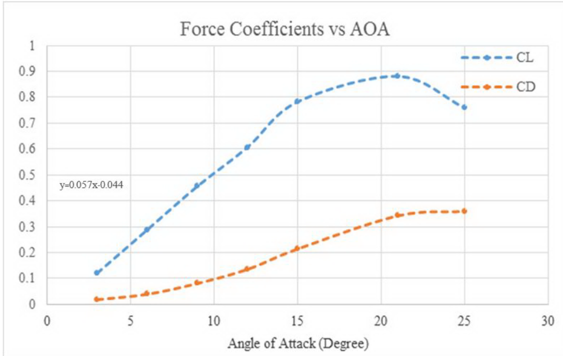

Figure 10: Force coefficient vs angle of attack.

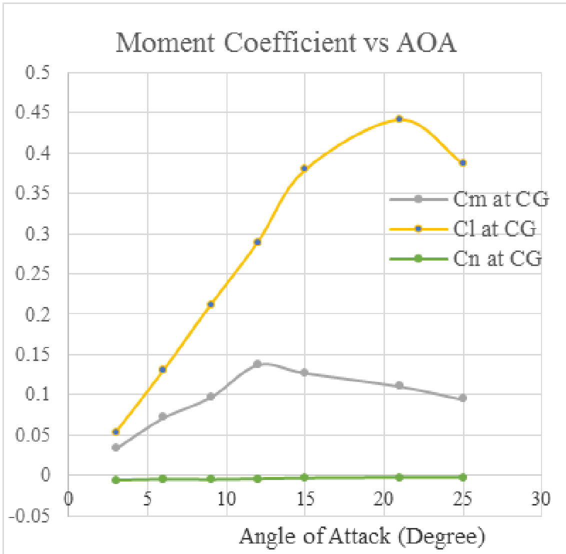

Figure 11: Moment coefficient vs angle of attack (left) and lift to drag ratio vs angle of attack (right).

Lift curve slope illustrated in figure 10 represents 0.057 (1/deg.) that can account for 3.264 (1/rad). This figure is lift curve slope that compute from 0 to 15 degree, so this may not be linear graph. The recalculated lift curve slope from 0 to 6 degree which should be linear represents 2.744 1/rad (0.0479 1/deg). There is a decrease in the slope, however, it is closer to the lift curve slope of the rectangular flat plate that have same as the aspect ratio [7]. If the slope of flat plate and the designed wing compare to the Helmholds lifting line theory,

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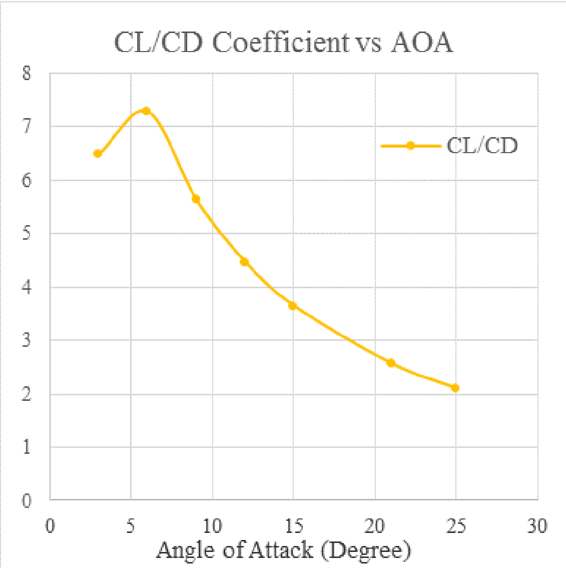

Figure 12: Moment coefficient vs angle of attack (left) and lift to drag ratio vs angle of attack (right).

the both errors shown in table 4 are insignificant difference. This may be because the equation is developed for low aspect ratio wings.

	Helmhold	Design wing	Flat plate
Lift curve slope	2.499	2.744	2.612
Error;percentage	-	9.817	4.543

Table 4: Lift curve slope.

Following step, the Oswalds efficiency factor (e) of the designed wing and the flat plate was computed to show the performance of the two wings from Prandtl's lifting line equation [6]. The figures illustrated that the design appears to be better performance than the rectangular flat plate. This may be the result of the strange shape that can produce the suitable flow.

(AoA 0-6deg)	CL(alpha) ;per deg	CL(alpha) ;per rad	Oswald factor
Designed wing	0.0479	2.744	0.820
Flatplate	0.0456	2.612	0.7532

Table 5: Oswalds efficiency factor.

3.2 *Rolling moment generated from the folding wing*

After folded the wing according to the models in section 2.6 and simulate them to calculate the moment that was created in each model, the both table 8 and figure 12 indicate the relationship between generated rolling moment (in term of rolling coefficient,) and the ratio of left and right wing area. It can be seen that the rolling moment increases when the differential area goes up. In the first state, it is symmetrical wing, so the coefficient of rolling moment is getting close to zero. Then the wing was folded, the area ratio changed. This results from an asymmetric lift force between two sides. The right wing has more area than the left, then the rolling moment was generated. When the different area increases in the second and third model, this results in a noticeable rise in the rolling moment.

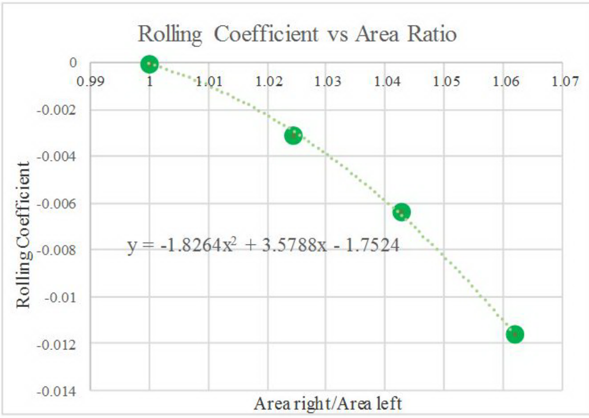

Figure 13: Relationship between rolling coefficient and area ratio.

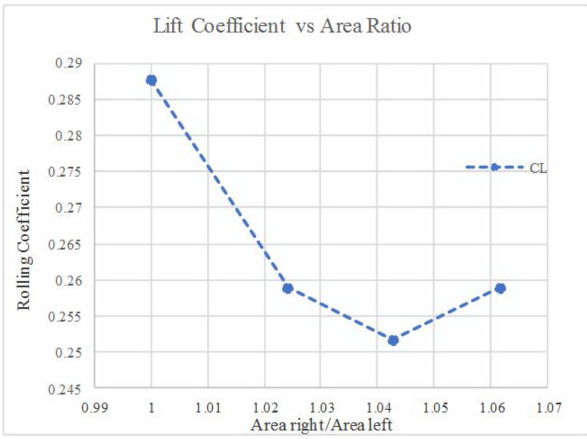

Figure 14: Relationship between CL and area ratio.

Furthermore, the relationship between lift coefficient and area ratio (figure 13) of this wing are in the range from around 0.285 to 0.25, so the required lift of the plane (0.274) is in this range. That mean this plane have enough lift to operate in rolling condition. Another relation between rolling coefficient and area ratio in figure 14 and equation on the graph meet the required rolling moment that was -0.00349 when the area ratio is 1.0279.

4 CONCLUSION

In conclusion, the study of this wing without folding is show the trim angle of attack and other significant aircraft characteristics. This will increase developers confidence to make the actual model of this aircraft. Another section about the folding wing indicates the positive result of the relation between the rolling coefficient and the area ratio of two side of wing. This convinces the developer that the folding aircraft is maneuverable by their structure without any rolling control surface.

ACKNOWLEDGEMENTS

This research could not acheived without the support from the Center of Innovative and Integrated of Mini and Micro Air Vehicle and other peoples in the Department of Aerospace Engineering, Faculty of Engineering, Kasetsart University. Authors would like to thank for the partial funding of registration fee for the conference from the Graduate School , Kasetsart University.

Figure 15: CiiMAV, Department of Aerospace Engineering, Kasetsart University

REFERENCES

[1] S.Kaewsutthi C.Thiptopas and A.Tohwae a yee. High performance propeller system for a multi-mission micro aerial vehicle. *International Journal of Micro Air Vehicles*, 5(3):179–191, 2013.

[2] J.M.Moschetta K.Chinwicharnam, D.Ariza and C.Thiptopas. Aerodynamic characteristics of a low aspect ratio wing and propeller interaction for a tilt-body mav. *International Journal of Micro Air Vehicles*, 5(4):245–260, 2013.

[3] M.J. Bamber. Aerodynamic rolling and yawing moments produced by floating wing-tip ailerons, as measured by the spinning balance. In *National advisory committee for aeronautics*, 1934.

[4] D.M. Rao and H. Va. Leading edge flap system for aircraft control augmentation. In *United States Patent, 4485992*, 1984.

[5] R.C. Montgomery D.L. Raney and L.L. Green. Flight control using distributed shape-change effector arrays. In *AIAA Paper*, 2000.

[6] P.G. Ifju. Flexible-wing-based micro air vehicles. In *WIT Transactions on State of the Art in Science and Engineering*, 2005.

[7] T.J. Mueller. Aerodynamic measurements at low reynolds numbers for fixed wing micro-air vehicles. In *Hessert Center for Aerospace Research, University of Notre Dame*, 1999.