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Research paper

The Effect of Wing Margin Shape Generalisation on the Aerodynamic Performance of a Bat Inspired Wing

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Abstract

Bio-inspiration is a method of design that uses findings and observation from the field of biology and applying them in mechanical applications. In this study, bio-inspiration was used to develop a flapping wing for a Micro Air Vehicle. This is done by producing a wing geometry by tracing the margin shape of the wing. The trace was then used to generate vertices of 99, 49, 13, and 7 vertices. The vertices were then used to create a CAD drawing to calculate the lift, drag, and aerodynamic efficiency for each generated wing. The wing was set at 20 degrees angle of attack with a flapping frequency of 3Hz. The wing was set to increase and will then correlated to increasing advance ratio of 0.19 to 5.19. The results shows that each wing behaves similarly generating the highest lift at low advance ratio, and the generated lift decreases as the advance ratio increases. At low advance ratios, 99, 49, and 13 vertices wings have similar generated lift while 7 vertices wing has the lowest lift generation. However, at high advance ratios, the 7 vertices wing has the highest generated lift followed by the 13 vertices wing, and then the 4 vertices wing. The 99 vertices wing has the lowest generated lift. Similar patterns is observed for drag where at lower advance ratios, 7 vertices wings generates the least drag followed by 13, 49, and 99 vertices wing. At higher advance ratios, 99 vertices wing generates the least drag followed by 49, 13, and 7 vertices wing. As for aerodynamic efficiency, 7 vertices wing has the highest lift to drag ratio followed by 13, 49, and 99 vertices wing. This is due to the wing geometry's ability to generate wing tip vortex at high advance ratio. The study has shown that the act of geometry simplification can be used to improve upon a bio-inspired design.

Keywords: *Flapping Wing, Micro Air Vehicles, Bio-Inspiration, Computational Fluid Dynamics.*

1. Introduction

Bio-inspiration is a recent method of design where observations learned from the natural world is used to solve problems in different fields, including mechanical or engineering applications [1]. In this study, bio-inspiration process was used to develop a Micro Air Vehicle. Which is defined as an unmanned aerial vehicle that have a wing span of 15cm. MAVs have multiple applications that spans from military and civilian which includes industrial inspections in small and tight spaces, and indoor reconnaissance [2].
However, MAVs' small size pose a significant challenge to designers and engineers. This is due to MAVs' flight missions in small and tight spaces, this means that the aircraft needed to have the agility and manoeuvrability that allows it to fulfil its mission. A possible solution to this problem are flapping wings. This is because flapping wings can generate lift without much forward flight and can practically hover which makes it manoeuvrable like rotary wings, but it can also glide, and it operates at lower frequency than rotary wings which makes it efficient like fixed wings. However, there are few examples of a successful man-made flapping wing. Therefore, examples from biological flapping wings is needed, this is where bio-inspiration design comes in.
An example of a successful flapping wing in nature are bat wings. Bats are known to fly in-doors and capable of complex manoeuvres. While at the same time, they are known to fly over long distances and even migrate to faraway places. This means that bat wings are both efficient and manoeuvrable and the reason for bat wings is used for the basis of the bio-inspired wing in this study. The objective of this is to study the effect of wing shape geometrical simplification on the lift generation of a bat inspired flapping wing.

2. Literature Review

2.1. Bio-Inspiration

An important part that needed to be understood when it comes to bio-inspiration is that biological systems are complex and even a single cell organism has complex properties that is not necessarily fully understood. However, according to G.M. Whitesides, 2015 [1] a biological system does not need to be fully understood to be applied in a mechanical application. Plus, for bio-inspired studies, the simplest method can be the best one. Physical observations like muscle actuation and flight behaviour, observations that are already well defined in a specific target of interest is enough for a bio-inspired study. For this study, here are the several physical observations found in a real-life bat that will be used.
An important part of a bat wing observation is the structure of the wing itself. According to Swartz et al., 1996 [3], a bat wing can be sectioned in to several regions with each region plays a role in a

bat flight (as seen in Fig. 1); the *plagiopatagium* (the proximal region of the wing, the *dactylopatagium* (the prehensile hand region of the wing), and the *uropatagium* (the tail membrane). The *plagiopatagium*, has the greatest function when it comes to generating lift and is where the centre of lift is located. The *dactylopatagium* plays a more important role in manoeuvrability and generating thrust. While *uropatagium* also plays a role in lift and thrust generation. The role of each region can be attributed to the mechanical properties of the region itself where the wing is found to be anisotropic in nature. The wing is more along the trailing edge but stiffer parallel to the wing skeleton. The regions role in the lift generation can also be attributed to the wing geometry itself where the wing shape determines to location of the centre of lift.

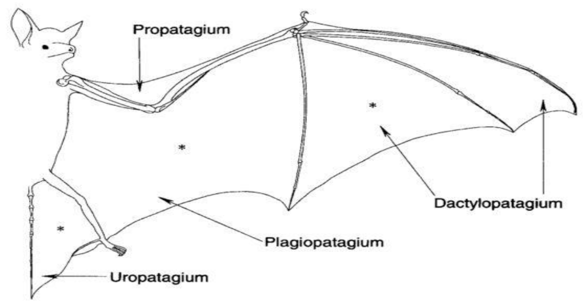


Fig. 1: Bat wing regions [3]

Another part of understanding a bat wing is to understand how a bat flies in nature and what the flight performance capable of a natural bat are. In a study done by E.K.V. Kalko, 1995 [4], it was shown that during insect pursuit, the capture and retrieval manoeuvre of a specific type of a bat usually last for less than one seconds and only occasionally last for more than one seconds, this shows the manoeuvre capability of a bat flight. In the same study it was also shown that in an open space flight, the search flight of a bat ranges from 4.2 m/s to 7.1 m/s. During pursuits, the search flight speed drops down to 1.5m/s to 3.5 m/s, and at high pursuits, the flight speed drops to 0.25m/s to 0.5m/s. The pursuit speed of a bat depends on the type prey they are pursuing, where 0.5m/s to 1 m/s for small insects such as mosquito and 3m/s to 4m/s. This gives us a range of flight speed for a bat flight from 0.25m/to 7 m/s.

In terms of flapping characteristics, a study done by P. Watts et al., 2001 [5] have shown that the flapping frequency of a bat flight ranges from 3Hz to 7 Hz. In that study it was also shown that the flapping motion is more complex than a simple sinusoidal flapping motion. A natural bat wing flaps in a folding in and out motion with the wing area almost double during the downstroke motion and the wing area contracts during the upstroke motion (as can be seen in Fig. 2). This is because it is to minimize the negative lift forces of the upstroke motion while maximizing the positive lift of the downstroke motion. These observations done by previous works will be the basis for the bio-inspiration done in this study.

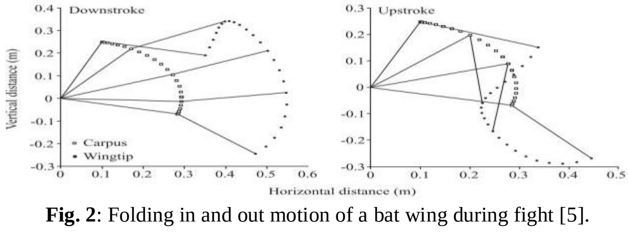


Fig. 2: Folding in and out motion of a bat wing during fight [5].

2.2. Wing Aerodynamics

Another important part to consider for this study is the previous observations of other bio-inspired works done for bat wings especially when it comes to the aerodynamics of a bat wing. A previous work that focused on the effects of a bat wing structure on its aerodynamic performance have been done by H. Yusoff et al., 2014 [4] where, it was shown that flexible wings can increase the lift and the stall angle. The study have also shown the effect of high free-stream where it will cause an increase in drag and increase in membrane vibration.

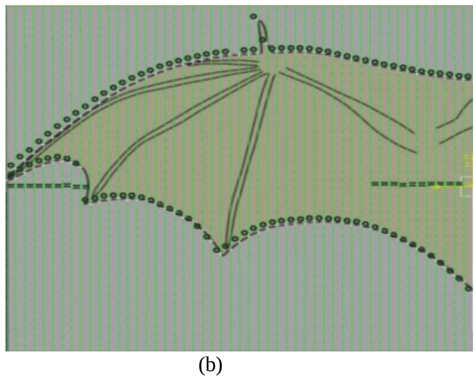
H. Yusoff et al., 2015 [5] also have shown the effects of wing camber where the lift increases with increasing wing camber but only at low freestream velocity. H. Aono et al., 2013 [6] shows that force generation can be enhanced by stabilizing the leading-edge vortex. S. Tobing et al., 2017 [7] noted that rigid wings have the highest efficiency but produces the most drag. The most interesting findings when it comes to wing flexibility can from W. Tay et al., 2017 [8] that shows different directions of wing flexibility can have different effects where, rigid wing span and flexible chord can generate more lift with low power.

Notice that most of the previous study mainly focused on the effects of the flexibility of the wing itself. While wing flexibility is not the focus of this study wing flexibility does have a correlation with the wing shape itself since it determines the shape of the wing while under aerodynamic forces. The main take away from the previous studies is the effect of wind speed and flight condition on the lift generation of the wing and the role of wind vortex on the lift generation of the wing. The focus on wing flexibility itself is a gap in knowledge since it is the wing shape that determines the aerodynamic properties of a wing. The wing flexibility determines the shape of the wing. This gap is a motivation for this study.

3. Methodology

3.1. Wing geometry

One of the challenges of this study lies in translating the forms of a natural wing and apply it to a mechanical application. As mentioned before it is not the goal of a bio-inspiration study to make a one to one scale of a bat wing, it is not impossible, but it will be too difficult of a practical application. As mentioned before for a bio-inspired study to be practical, a level of abstraction and generalization is needed. For this study, the shape of the model bat wing will be taken from the margin shape of a natural bat found in a study done by T.Y. Hubel et al., 2009 [9]. While the wing is not a real wing, but it is a representation of an average wing. The original wing shape is a spread natural bat wing (Fig. 3). The wing will then be segmented (Fig. 3) and several points will be generated at the margin (or outline) of the wing. The points will then be used to generate a curve that takes the margin shape of the wing. The curve will then be used to generate a flat wing using CATIA CAD software that will act as a wing model.



(b)

Fig. 3: The wing segmented for the CAD generation based on wing shape from T.Y. Hubel [9].

The generated wing was all set to have a wing span of 15cm and the wing were flat with the thickness of 1mm. 15cm wing span

was chosen since it is the defined wing span for a MAV and the wings were flat because this study aims to study the effect of wing margin and the effect of abstraction of the margin shape.
Using this method, the process of geometry simplification can be achieved. This is done by sequentially removing the points that is being used to make the curve and this will create a more simplified and more abstracted version of the wing geometry. The number of points that was used to create the wing margin shape was 99, 49, 13, and 7 (as seen in Fig. 4).

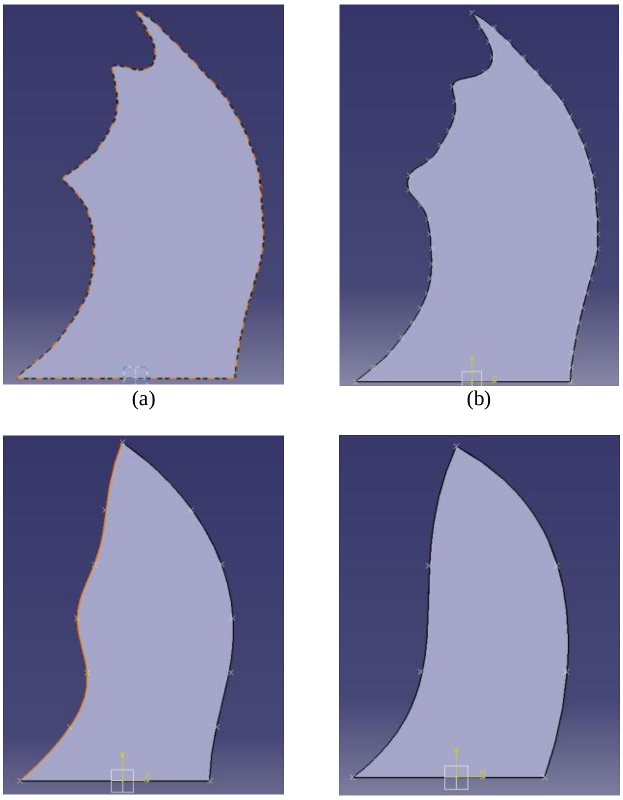


Fig. 4: Generated wing geometry where; (a) is the 99 vertices wing, (b) is the 49 vertices wing, (c) is the 13 vertices wing, and (d) is the 7 vertices wing

The wing area of each wing was; $0.008m^2$ for 99 vertices, $0.008m^2$ for 49 vertices, $0.009m^2$ for 13 vertices, and $0.009m^2$ for 7 vertices. The thickness of the wing was 1mm and the length from root to tip was 15cm.

3.2. Wing motion

Another important part of the study will be the flight parameters of the flight. As mentioned before, according to E.K.V. Kalko, 1995 [4], a normal flight of a bat during insect pursuit the flight speed can be at a range of between 0.25m/s to 7m/s and according to S.M. Swartz et al., 1996 [3] the flapping frequency averages at around 3Hz to 12Hz. This means that the test parameters will be based on previous observations of real life bats. Therefore, for this study the bat flight will be observed at 0.5m/s, 1m/s, 3m/s, 5m/s, and 7m/s at flapping frequency of 3Hz.
Instead of the result of the final generated lift, drag and aerodynamic efficiency be calculated against changing wind speed, this simulation was done against changing advance ratio. Advance ratio is a dimensionless value which is the ratio of the forward speed to the flapping frequency. Advance ratio is given as:

$$J = \frac{U_\infty}{2fb\theta} \quad (1)$$

Where;

U_∞ is the freestream velocity
θ is the flapping angle
f is the flapping frequency
b is the wing span

When the advance ratio is less than 1, then the flight is in the unsteady state regime, which means that the flapping motion is more dominant than the forward motion. When the advance ratio is more than 1, then the flight is in the quasi-steady state regime, which means that the forward flight is dominant. The changing flight parameters in this study will cover different flight regimes from unsteady to quasi-steady flight regime.

3.3. CFD Simulation

The airflow around the wing is studied through computational fluid dynamics (CFD) simulation that uses the Navier-Stokes equation as its governing equation. The whole simulation will be done using Fluent as its solver. The model was assumed to be steady state and incompressible where the air is assumed to be ideal air at standard sea level air properties.

3.4. Mesh Generation

For the simulation to be done, a mesh flow filed must first be generated. For this study, a 0.5m X 1m X 4m flow field was generated. This study used unstructured mesh and the mesh size was set at fine where the mesh generated around 25,000 nodes, as seen in Fig. 6. Unstructured mesh was used instead of a structured one because it is easier since the simulation deals with dynamic meshing. Dynamic mesh was used because the wing moves in a flapping motion and a transient calculation was done. The mesh will re-layer and re-mesh as the wing flaps. This is done to keep the skewness of the mesh at around the same level.

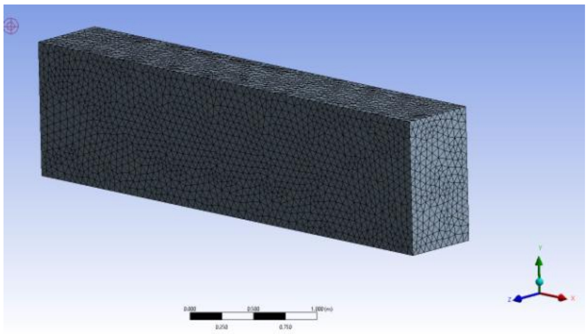


Fig. 5: Generated mesh.

4. Results

4.1. Lift Generation

In this study, the lift generation of a flapping wing at different wind speed. The different wind speed will be measured in a non-dimensional value called advance ratio.

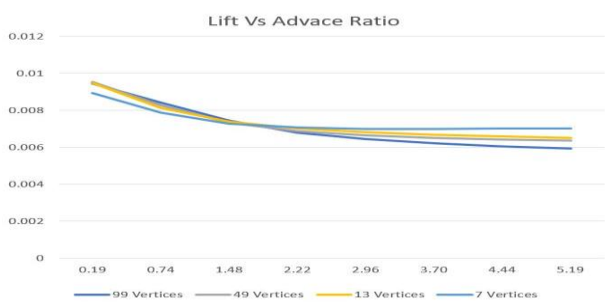


Fig. 6: Advance ratio Versus Averaged lift generated

As seen in figure, each the averaged lift generation for every wing changes with advance ratio the same way. As the advance ratio increases and moves into a steady state flight regime, the averaged lift generation decreases until a certain point where the drop starts to level out and the lift generation changes little with increasing advance ratio.

As mentioned before, advance ratio is a measurement of the ratio between the flapping frequency and the forward wind speed. As the advance ratio increases, the forward wind speed becomes more dominant and the flapping wing acts more like a conventional fixed wing. This drop in averaged lift as the advance ratio increases is consistent with a study done by H. Yusoff, 2016 [4].

In terms of the difference in lift generation for the different wings however, at advance ratio of 0.19 (unsteady state flight regime), 99, 49, and 13 vertices wings all started around the same lift. The 7 vertices wing has a lower lift generation than the other wings. However, as the advance ratio increases (and as the flight changes into quasi-steady flight regime), the lift generation values started to separate and at advance ratio 5.19, the 7 vertices wing has the largest lift generation followed by 13 vertices wing, 49 vertices wing, and 99 vertices wing.

2.4.2. Averaged Drag

Fig. 7 shows the change of drag with changing advance ratio. Like change in lift, as advance ratio increases, the drag decreases and the rate also decrease as advance ratio increases and levels out at later advance ratio. Also like generated lift, at low advance ratio, at unsteady state flight regime, 7 vertices wing generates the least drag followed by 13 vertices wing, and 49 vertices wing and 99 vertices wing has the highest drag at around the same level. At higher advance ratio, the order is reversed where, 99 vertices wing generates the lowest drag followed by the 49 vertices wing, the 13 vertices wing, and the 7 vertices wing generates the most drag.

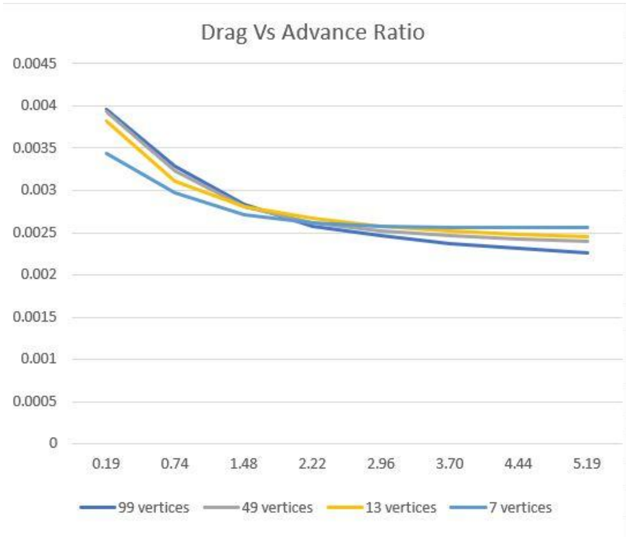


Fig. 7: Drag Versus Advance Ratio

4.3. Aerodynamic Efficiency

The aerodynamic efficiency of a wing can be measured by the ratio of the lift generated and drag. Fig. 8 shows the change in aerodynamic efficiency with changing advance ratio. From the obtained result it is observed that 7 vertices wing has the highest overall lift to drag ratio followed by 13 vertices wing, then 49 vertices wing, and 99 vertices wing has the lowest lift to drag ratio. Also observed in the recorded result, the lift to drag ratio is lowest at lower advance ratio but as the advance ratio increases, the lift to drag ratio also increases but the curve starts to level out at higher advance ratio. This is true for all wings.

Interestingly, 7 vertices wing has the lowest increase in lift to drag ratio as the advance ratio increase. All other wings have a higher steep curve when the advance ratio increases from 0.19 to 1.48, or as the flight regimes changes from unsteady state regime to steady state regime. Also observed, the lift to drag ratio for 99 vertices wing started to decrease after 1.48.

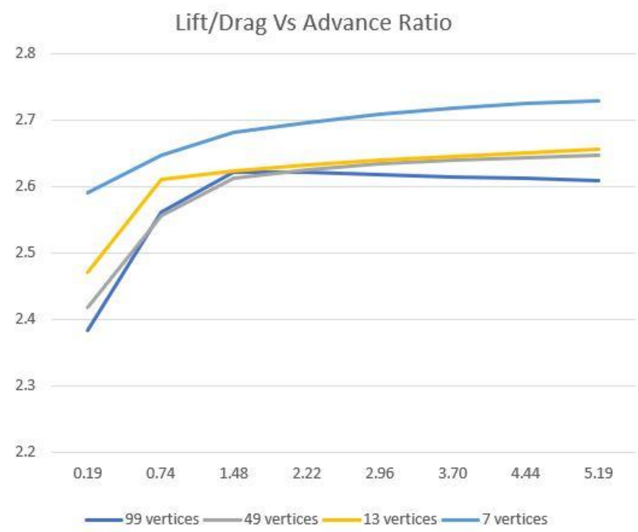


Fig. 8: Aerodynamic Efficiency, Lift/Drag Versus Advance Ratio

This observation is consistent with another study done by F.T. Muijers et al., 2012 [10], where the aerodynamics performance of a swift is compared to the aerodynamic performance of a bat wing. In that study it was shown that swift wings have better lift generation during gliding while bat wings have better lift generation during flapping flights.

Similarly, in this study, 99 vertices wing, which is modelled closest to a real bat wing has a better lift generation at lower advance ratio flights, where the flapping flight is more dominant. But at higher advance ratio, where the forward speed is more dominant, and the flight becomes closer to gliding flight, the lift generation for the 99 vertices wing decay a lot more.

The opposite is true for the 7 vertices wings, which is the furthest from an actual bat wings and the wings is more swept and featureless. At lower advance ratio, where the flapping flight is dominant, the lift generation is lower. While at higher advance ratio, where the flight is like gliding, the lift generation is higher.

According to F.T. Muijers et al., 2012 [10] this is due to the wake structure that its formed by the wings during flight and the formation of the wing tip vortices that contributes to the lift generation especially during glide flights.

Interestingly, 49 vertices and 13 vertices wings have similar lift generations. Plus, at lower advance ratio, 49 vertices and 13 vertices wings have similar lift generation to 99 vertices wings while still have a higher lift at higher advance ratio. A possible explanation for this is due to 49 vertices and 13 vertices wings are a halfway point between the 99 vertices wing's accurate wing shape and the 7 vertices wing's simplified wing shape. Both 49 and 13 vertices wings still have features particularly at the trailing edge off the wing that might contribute to the lift generation especially at lower advance ratio.

5. Conclusions

The data have shown that the wing geometry simplification can influence the lift generation of the wing. Since the wing area is not that different, the different aerodynamic performance can be attributed to the wing geometry. Overall 7 vertices wing have the best aerodynamic performance, but 99 vertices wing have the most lift at lower advance ratio. There is no clear conclusion of which wing has the best performance and there are several blind spots to the study such as, the lift generation at other angles of attack, the effect of wing flexibility, and other aerodynamic factors such as drag and thrust. All these factors give a possibility for future studies.

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