Group 1

STUDY ON FLEXIBILITY OF FLAPPING WING

Term Paper Report

Viscous Flow Theory (AE31010)
Autumn 2023

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ABSTRACT:

The flight of any insect is a considerably complex topic. And the flexibility of the insect wing is just one of the myriad of layers of complexity in the problem which has direct and indirect effects on the aerodynamics of the wing. The flexibility of a wing can be varied in two ways : spanwise flexibility and chordwise flexibility. And it is seen that changing each of these affects the lift characteristics differently. However our experiment is more broad, in the sense that we only increase the overall modulus of rigidity of the wing material by stacking mylar sheets and we observe how that affects the amount of lift generated. The lift is measured using an arduino operated force sensor, by measuring the variation of the force that the model exerts on the ground. We see that among the wing sets with 1,4 and 7 mylar sheets the lift produced was greatest for the set with 4 mylar sheets stacked.

INTRODUCTION:

We attempt to study how the rigidity of the wing material affects the lift and drag characteristics of a dragonfly inspired tandem wing flapping model. Multiple simulatory and experimental studies have already suggested that there is an improvement in these characteristics. We, in our study here, attempt to verify and, in our own way, quantify these results. Wings flapping at high angles of attack generate stable leading edge vorticity, which persists throughout the duration of the stroke and enhances mean aerodynamic forces. These aerodynamic forces can be controlled by altering the flexibility of the flapping wing. Both spanwise and chordwise flexibility have significant effects on the aerodynamics of these wings.

We aim to develop a flapping wing model, with a system for easy wing changing, to study how wing flexibility affects its aerodynamic performance. Our approach involves modifying the wing's flexibility by stacking mylar sheets in varying layers—specifically, 1, 4, and 7 layers. The analysis of these modifications will be based on force readings obtained using a force sensor.

BACKGROUND:

The flexibility of wings plays a vital role in the intriguing realm of insect flight. Previous research has highlighted the existence of an optimal flexibility range crucial for propulsion, with factors such as angle of attack, plunge frequency, amplitude, and Re influencing this range. Notably, wing flexibility has been observed to impact the size, strength, and temporal evolution of vortical structures around the wing, while also preventing flow separation and delaying stall.

Experiments and studies have unveiled the adaptive capabilities of flexible wings to various flight conditions, including turbulence and gusts. This adaptability, achieved through wing flexion and shape adjustments, contributes to enhanced aerodynamic performance and reduced fuel consumption. In the realm of insects, wings are characterized by their lightweight and flexible nature, enabling them to deform and respond to aerodynamic forces during flight. This inherent flexibility proves instrumental in optimizing aerodynamic performance, facilitating efficient maneuvering and control.

One notable mechanism is the leading-edge vortex, which effectively delays stall by keeping airflow attached to the wing's upper surface even at higher angles of attack. This phenomenon enhances lift, a critical feature for insects that frequently alter their wing angles for maneuvers and hovering.

LITERATURE REVIEW:

Effects of chordwise flexibility in flapping wings:

Aerodynamic forces vs wing stiffness:

As wing flexibility increases, the drag coefficient experiences a reduction in magnitude. Consequently, flexible wings produce lower drag as their flexibility increases. Similarly, the magnitude of lift coefficients also diminishes with rising wing flexibility, but they reach a plateau at higher angles of attack. Beyond an angle of attack of 50°, flexible wings generate more lift than their rigid counterparts. The maximum lift coefficients for flexible wings are influenced by the flexural stiffness of the wings. However, when considering the combined effect on the net force acting on the wing's surface, there is a consistent decrease as wing flexibility increases. Thus aerodynamic forces reduce as trailing edge wing flexibility increases.

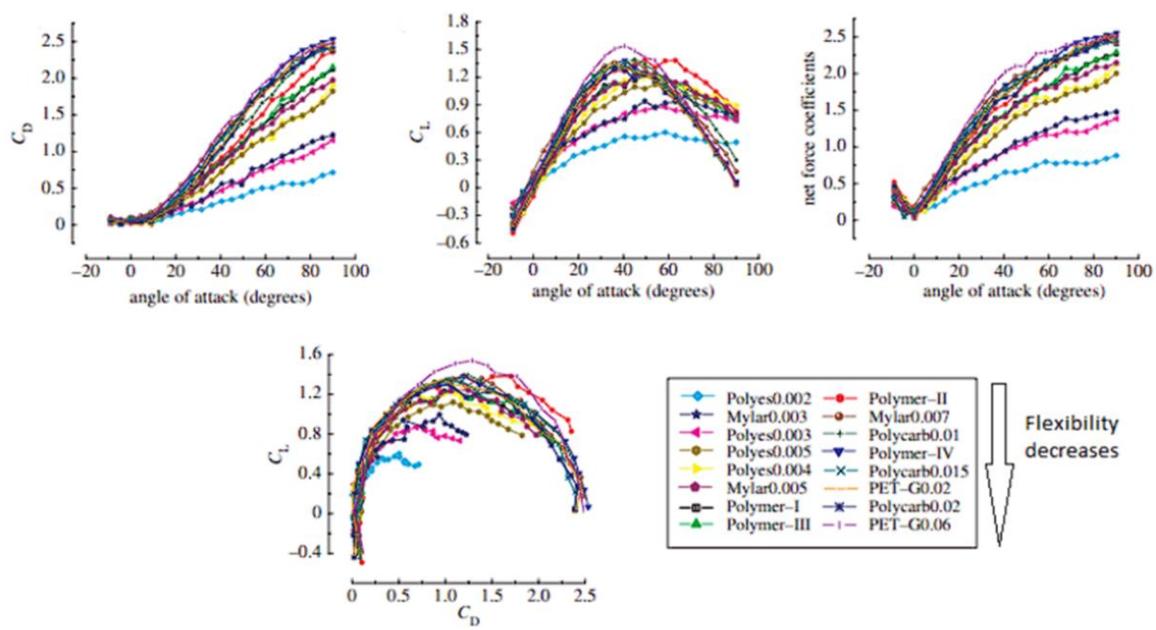


Fig 1 (Force coefficients versus angle of attack for different materials)

Impact of Flexural Stiffness on Lift-to-Drag Ratios:

The lift-to-drag ratios showed little sensitivity to changes in wing flexibility for lower angles of attack. This observation indicates that the overall forces on the wing were equally dampened, affecting both lift and drag generation to a similar extent. In terms of this performance measure, it can be concluded that at lower angles of attack, a flexible wing's ability to generate lift relative to drag is comparable to that of a rigid wing. Lift-to-drag ratios exhibited a greater sensitivity to wing flexibility when the wing was positioned broadside (at a 90° angle of attack). Consequently, a highly flexible wing, when moving broadside, had the capacity to generate substantial lift while concurrently producing less drag compared to a rigid plate. In essence, at extremely high angles of attack, flexible wings demonstrated superior performance when compared to their rigid counterparts.

Leading edge vortices:

The significance of the leading-edge vortex in enhancing force production in flapping wings is well-established, and its size typically correlates with the strength of the overall aerodynamic force generated by the wing. Since the bending or flexion of the trailing edge results in lower net forces compared to a rigid wing, it is likely that the leading-edge vortex in a flexible wing is smaller than that in its rigid counterpart. This suggests that the Kutta condition, which relates to the behavior of fluid flow at the wing's trailing edge, is more easily established when the flexible trailing edge realigns itself with the flow direction.

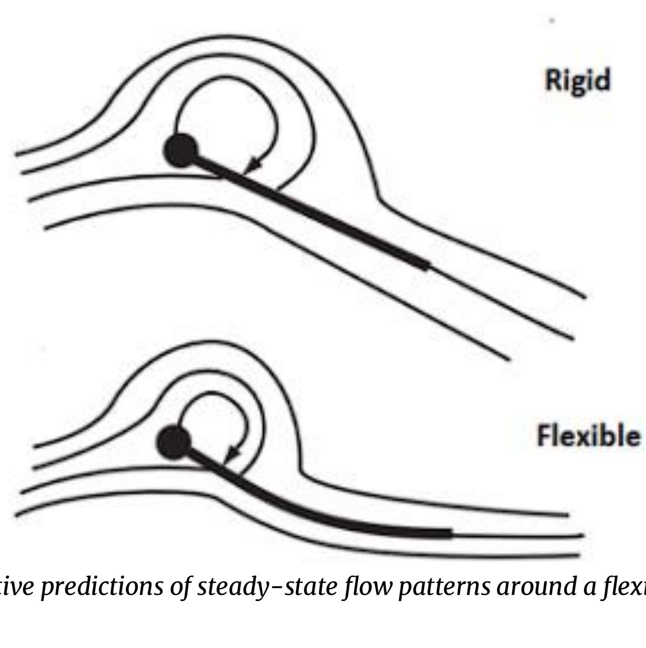


Fig 2 (Qualitative predictions of steady-state flow patterns around a flexible wing)

Effect of spanwise flexibility:

For Strouhal numbers greater than 0.2, a degree of spanwise flexibility was found to yield a small increase in thrust coefficient, and a small decrease in power-input requirement, resulting in higher efficiency. Introducing a far greater degree of spanwise flexibility, however, was found to be detrimental. A large phase delay of the wing tip displacement was observed, leading to the root and tip moving in opposite directions for a significant portion of the flapping stroke.

The variation of thrust coefficient with respect to reduced frequency of oscillation for airfoils and with time of different flexibility is shown below:

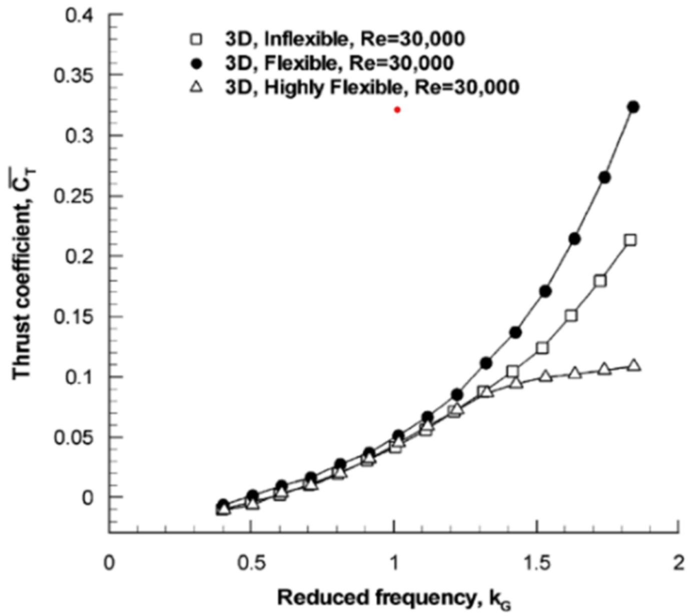


Fig 3 (Thrust coefficient as a function of Garrick frequency, Re=30,000)

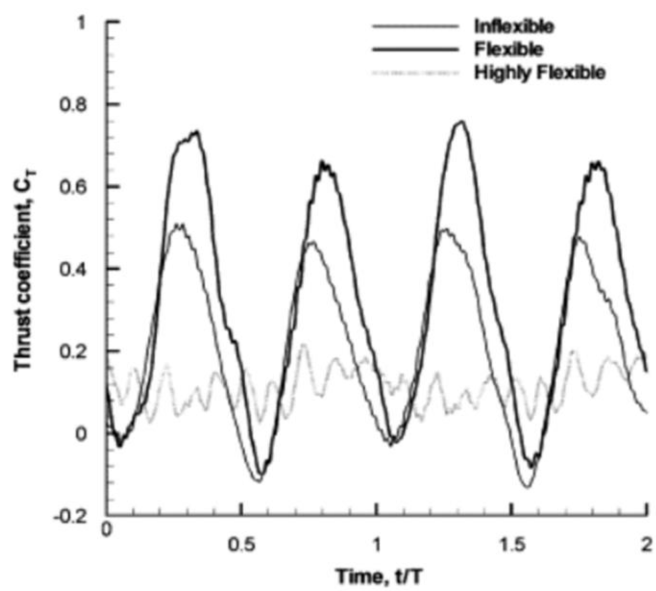


Fig 4 (Instantaneous thrust coefficient as a function of time over two heave cycles; Re=30,000, kG=1.82)

Near the tip, the vortices were observed to fork into two branches. Vorticity of opposing signs was observed to be shed from the root and tip. The corresponding vorticity fields revealed the formation of vorticity of one sense near the root, and of opposite sense near the tip, leading to a fragmented and weak vorticity pattern. The thrust coefficient was observed to be significantly reduced, and the efficiency diminished.

MATERIALS REQUIRED:

Chrome Plated Steel Rods, Carbon Fiber Rods, DC Motor, Batteries, Stainless Steel Dowel Pins, Bevel gears, 3D Printed CAD Models(Refer to Appendix for the CAD files), Mylar sheet(50 micron), Thin Wire, Arduino Uno, Force Sensor.

CAD MODELS:

LINKS 1 & 2:

Fig 5

PASSIVE ROTATION JOINT: (Right and Left):

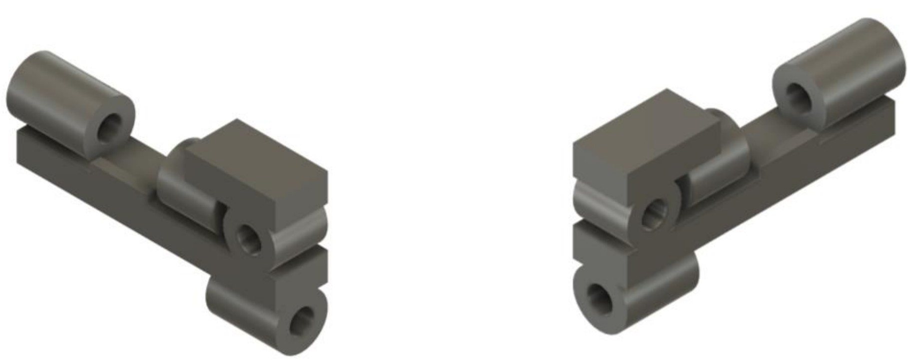


Fig 6

BASE: (different views):

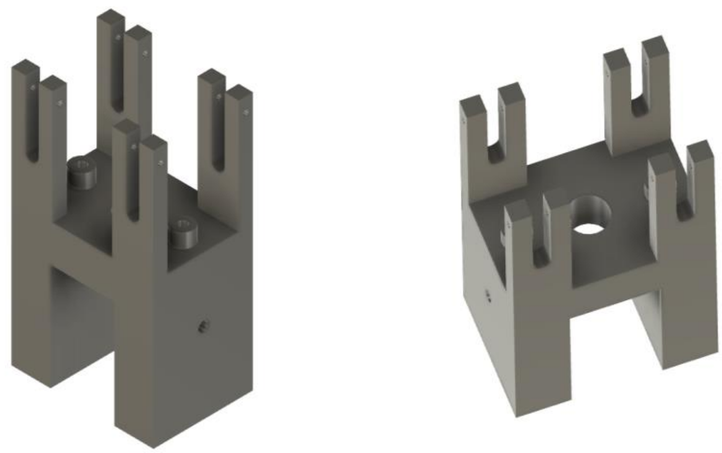


Fig 7

SLIDER:

Fig 8

ROTATING JOINT:

Fig 9

WORKING OF MODEL:

Due to the presence of bevel gears, as the motor rotates, it imparts rotational motion to link 1. The interconnected links and slider then convert this rotational movement into vertical translational motion. Essentially, this mechanism mirrors the functionality of a slider-crank mechanism. The slider executes an upward and downward motion, consequently driving the flapping motion of the wings.

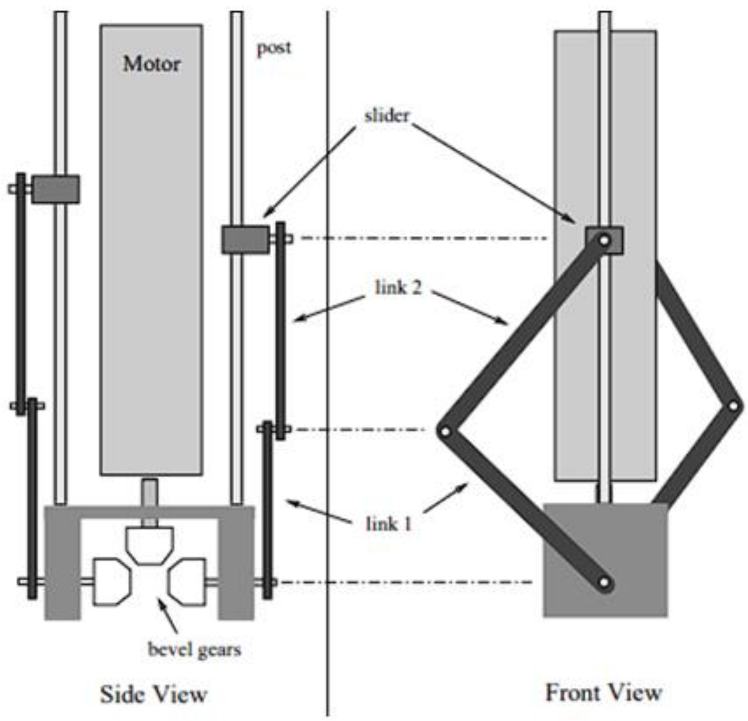


Fig 10 (gear mechanism)

Facilitating this motion is a passive rotation joint that enables the wing to revolve around the rod connecting it to the slider. It's worth noting that this rotational capability is constrained, limited to approximately 90 degrees of movement.

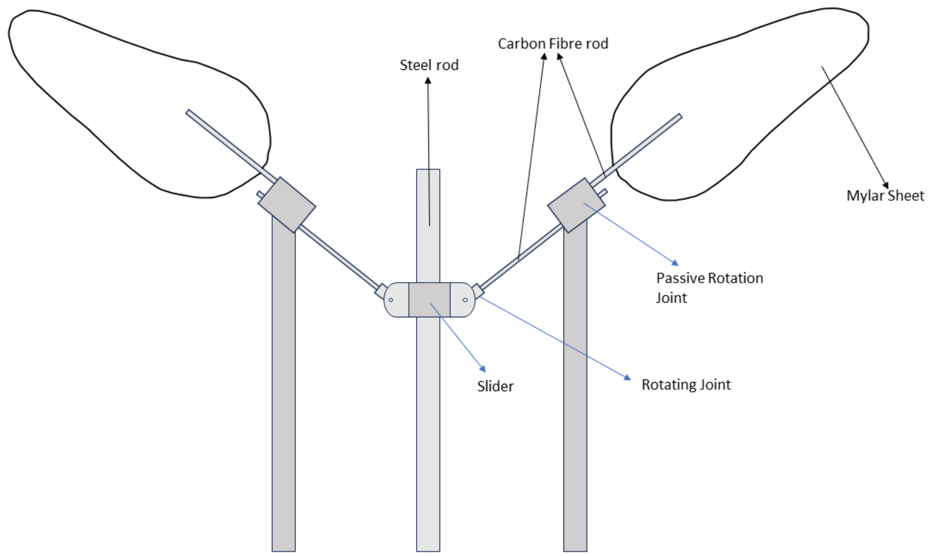
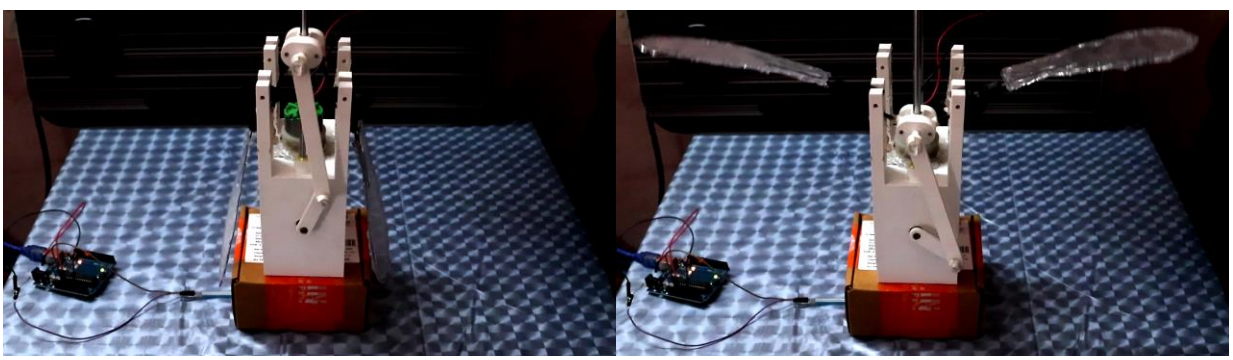


Fig 11 (front view of the slider mechanism)

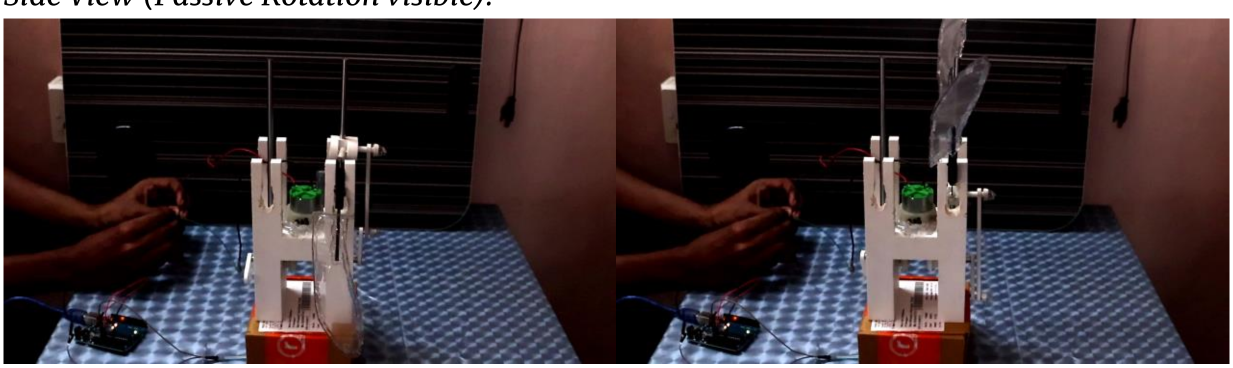
OBSERVATIONS:

Single layer (Wingbeat frequency = 1.5 Hz)

Front View:

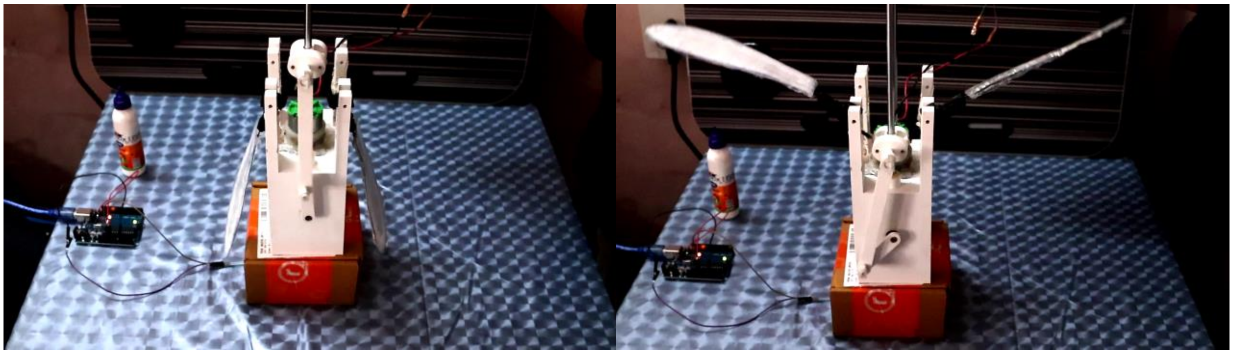


Side View (Passive Rotation visible):



4-layer (Wingbeat frequency = 1.5 Hz)

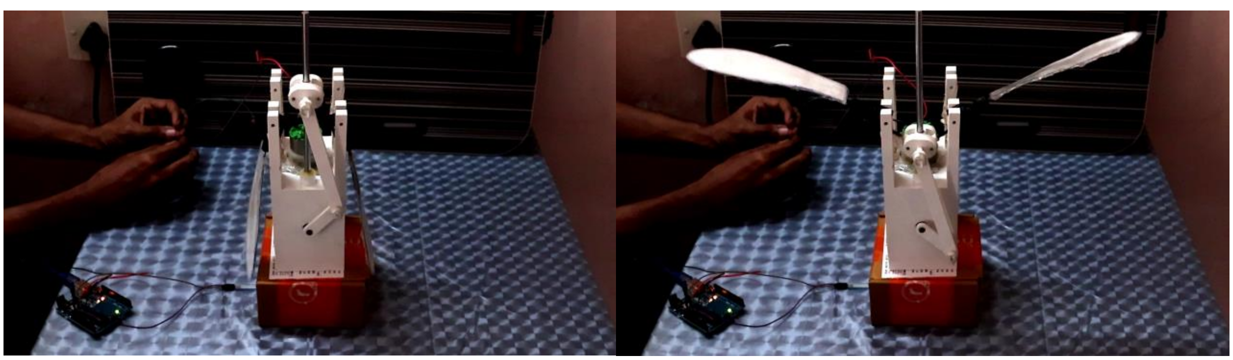
Front View:



Side View (Passive Rotation visible):

<u>7-layer</u> (Wingbeat frequency = 1.5 Hz)

Front View:



Side View (Passive Rotation visible):

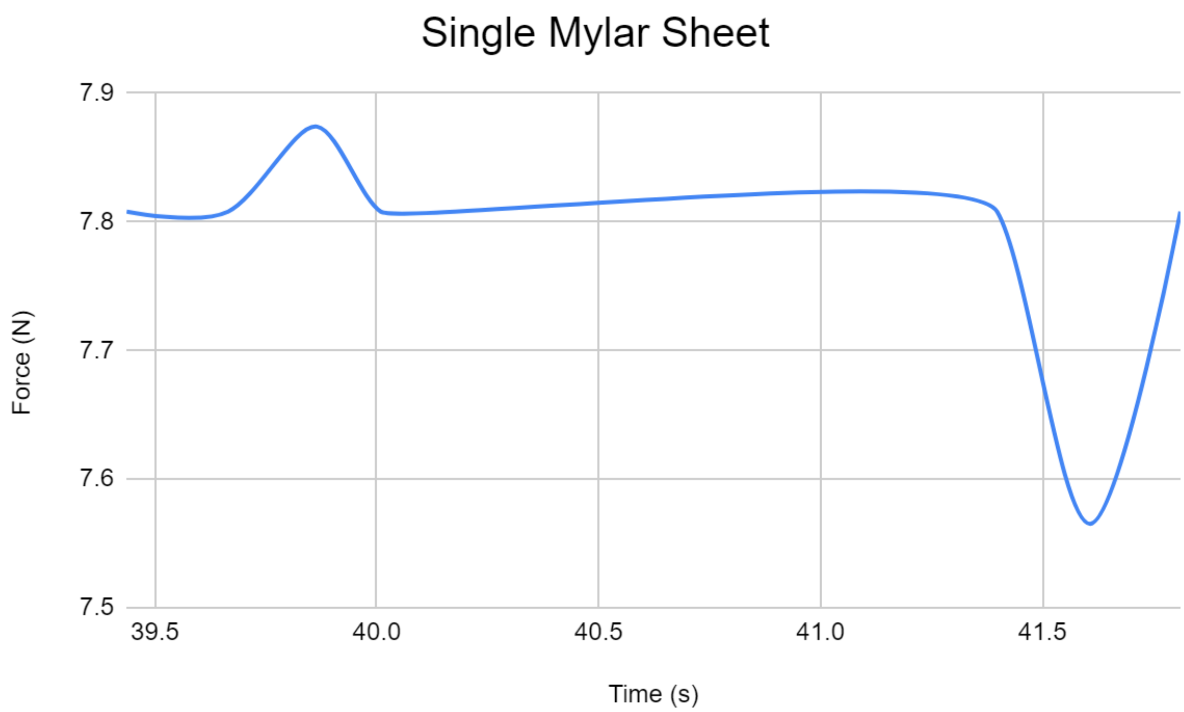
The videos distinctly highlight the passive rotational motion of the wings which play an important role in the lift generation mechanism. Even though the wings do appear to be flexible in the test videos, it is important to note that neither chordwise nor spanwise flexibility is visibly evident in any of the three cases. Therefore, our conclusions are grounded in the assumption that both these characteristics decrease as the number of mylar sheet layers increases.

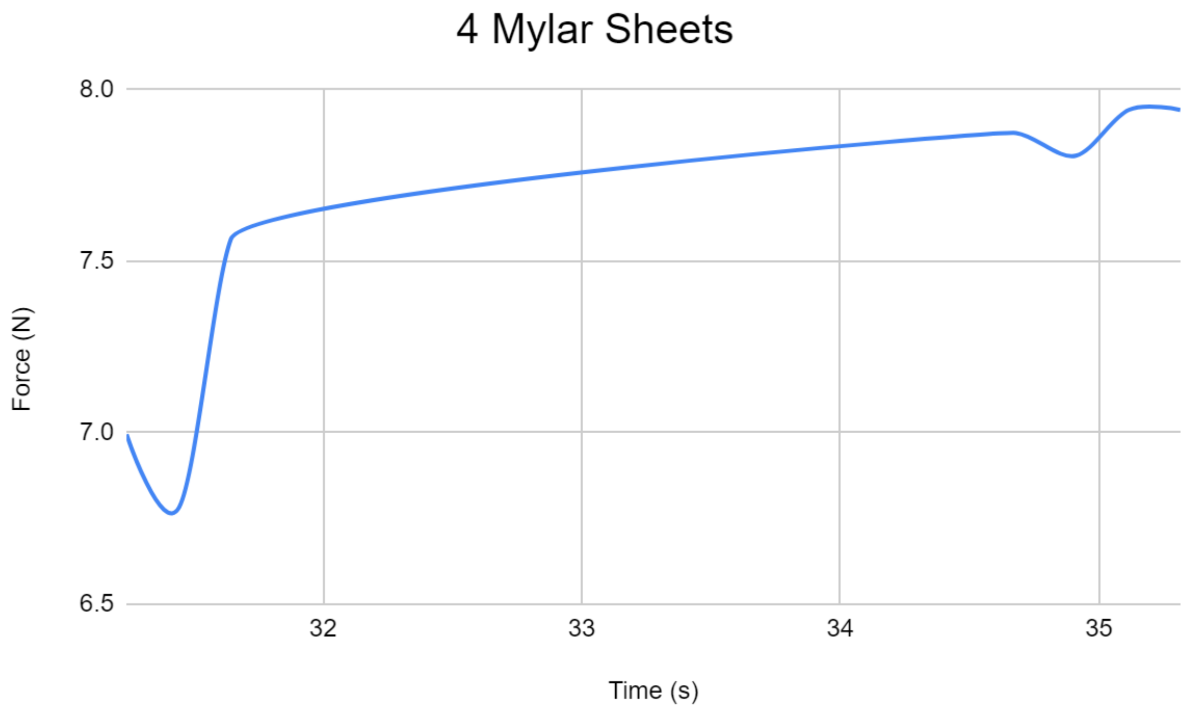
The link to the demonstration videos is present in the Appendix.

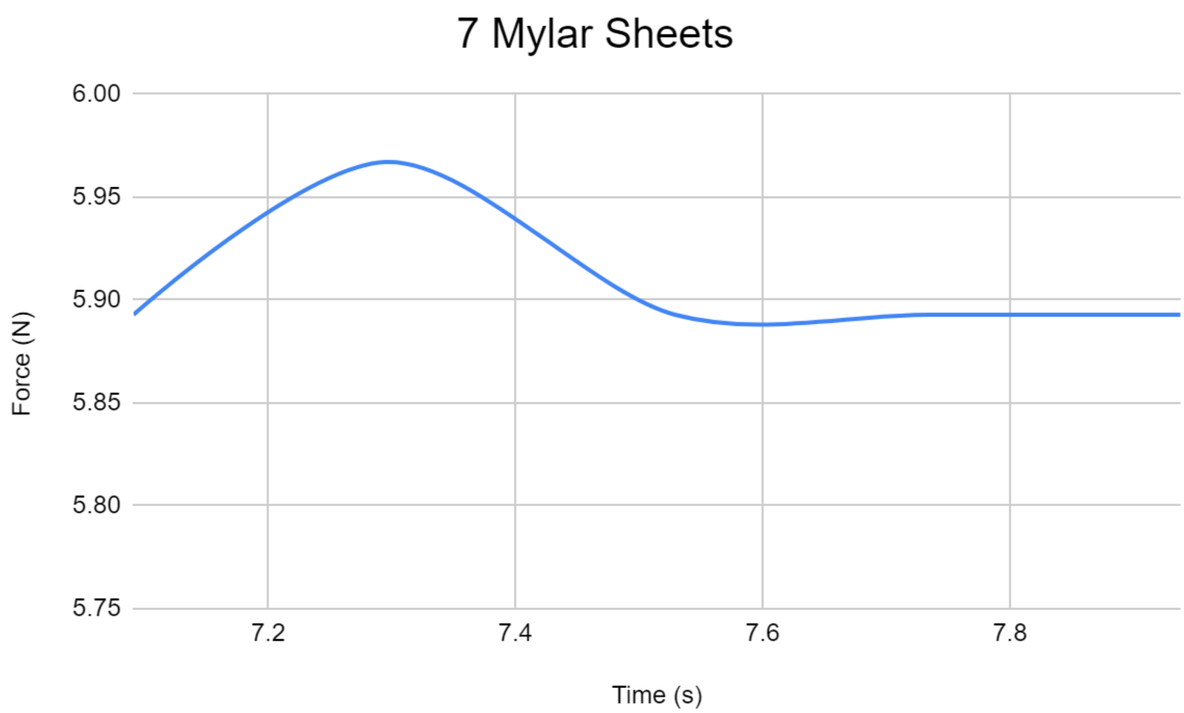
	Force(N):					
Before Flapping	Timestamp	Single mylar sheet	Timestamp	4 mylar sheet	Timestamp	7 mylar sheet
	30.851	6.447044	18.276	7.807971	47.537	4.925889
	31.965	6.543017	18.516	7.807971	47.768	4.987525
	31.965	6.543017	23.435	7.807971	47.968	4.956554
	33.102	6.447044	23.669	7.807971	48.203	4.987525
	34.194	6.494733	30.999	7.565233		—
After Flapping	39.436	7.807971	31.24	6.995383	7.091	5.892857
	39.665	7.807971	31.444	6.783419	7.295	5.96709
	39.865	7.874087	31.644	7.565233	7.529	5.892857
	40.009	7.807971	34.68	7.874087	7.735	5.892857
	41.398	7.807971	34.911	7.807971	7.938	5.892857

	41.608	7.565233	35.115	7.941176		—
	41.811	7.807971	35.315	7.941176		—

RESULTS AND DISCUSSION:







Analyzing the graph reveals distinct maximum and minimum values in the force data. It can be reasonably inferred that the minimum occurs during the downstroke (less downforce), while the maximum is observed during the upstroke (greater downforce).

The difference between these values can be interpreted as a suitable equivalent proportional to the lift force that is generated. Upon closer examination of the graph, it becomes evident that this difference is most pronounced for the wing with a 4-layer mylar sheet, surpassing both the single-layer and 7-layer configurations. Consequently, we can deduce that the average lift is highest for the wing with 4 layers compared to the other two configurations.

The graphs reveal a notable pattern: the increase in force observed during the upstroke is relatively less significant than the reduction in force witnessed during the downstroke. This phenomenon is caused due to the presence of passive rotation. During the downstroke, the wing aligns almost parallel to the ground. As a result, the force exerted by the air acts perpendicular to the ground. However, during the upstroke, the wing makes an angle with respect to the ground, causing only a component of the force to be perpendicular to the ground. As a result, the upstroke experiences a milder increase in force compared to the more significant decrease observed during the downstroke.

The absolute values of the forces are insignificant since they include inertial effects which cannot be accounted for accurately.

FUTURE WORK:

- Analyze flexibility effects across various materials with different thicknesses.
- Adjust wing chord and span to enhance visibility of flexibility effects.
- Improve passive rotational motion to closely mimic insect flight, especially inspired by dragonflies.
- Experiment with dual-wing configurations to understand flexibility in more complex setups.
- Implementing varied speeds during the upstroke and downstroke by employing a cam mechanism.
- Exploring the intricate relationship between wing deformation and vortex generation in insect flight.

INDIVIDUAL CONTRIBUTIONS:

Link for individual contribution statements by group members:
https://drive.google.com/drive/folders/19zmW6bdfZ1DJmWfztTwRyFrzNktTmcte?usp=drive_link

REFERENCES:

[1]Zhao, Liang, et al. "Aerodynamic effects of flexibility in flapping wings." Journal of the royal society Interface 7.44 (2010): 485-497.
[2]Heathcote, Sam, Z. Wang, and Ismet Gursul. "Effect of spanwise flexibility on flapping wing propulsion." Journal of Fluids and Structures 24.2 (2008): 183-199
[3]Shahzad, Aamer, et al. "Effects of flexibility on the hovering performance of flapping wings with different shapes and aspect ratios." Journal of Fluids and Structures 81 (2018): 69-96.
[4]Lang, Xinyu, et al. "Effect of wing membrane material on the aerodynamic performance of flexible flapping wing." Applied Sciences 12.9 (2022): 4501.
[5]Eberhard, M. J. (2016). "Aerodynamics of Insect Flight." In Handbook of Zoology: Arthropoda: Insecta: Coleoptera, Beetles, Volume 1: Morphology and Systematics (pp. 71-84).
[6]Dileo, Christopher, and Xinyan Deng. "Design of and experiments on a dragonfly-inspired robot." Advanced Robotics 23.7-8 (2009): 1003-1021.

APPENDIX:

CAD Models:
https://drive.google.com/drive/folders/1zkzQJ1BmZcqH0szUY2JIuBF0DqD-vq0J?usp=sharing
Readings and Graphs:

https://docs.google.com/spreadsheets/d/1Hhj2s9Lfp6iA_19uOk-m1RbUmR3_Qgwlacutmu04XMM/edit?usp=sharing
Demo Videos:
https://drive.google.com/drive/folders/1LZ0umRkRasB-yVpMNgAQW_Qny4T7Ud_a?usp=drive_link

GROUP MEMBERS:

1) Aswin D Menon (21AE10044)
2) Rahul Sunil (21AE10050)
3) Adithyan U S (21AE10049)
4) Anfal S (21AE10003)
5) Sagar K P (21AE30031)
6) Allwin Johnjo Prince (21AE10002)
7) Arjun Biju (21AE10007)

INDIVIDUAL CONTRIBUTIONS AND LEARNING STATEMENTS:

1) Aswin D Menon (21AE10044)-As the team leader, I was involved in the work from the start to the day of submission in both involving every team member in the making and testing of the model and contributing crucially to the overall work. In the beginning, I was involved in the literature review and contributed to the decision making process of how to make the wings flexible. I did the assembly of the flapping wing model. During this process, I took the time to make sure that every part is precisely bonded or attached with glue or pins, giving adequate time for the glue to dry. I also made sure that small flaws in the 3D printed models were taken care of by making small adjustments to the structure using soldering iron and other equipments. I also designed the wing, later made the wing from scratch using wires and mylar sheet and finally assembled the wing to the flapping wing model. Later, I did most of the test recordings and performed edits in the video clips wherever necessary. I also contributed in the compilation of information to make presentations and reports.

   In the course of the semester, I enjoyed the whole process, working together with the team members and learning a lot too. I got to understand and learn how the chordwise and spanwise flexibility affects the aerodynamic forces acting on the wing and learned that a certain level of flexibility is most favorable for efficient flapping wing flight. I have also gained problem solving skills during the process as we had to face many problems during the making and testing of the model. My skills in certain CAD, editing and coding softwares were also improved during the time period. Throughout, I have acquired valuable knowledge and skills that have significantly contributed to my intellectual and personal growth.

2) Rahul Sunil (21AE10050)-I was involved with determining the dimensions for the model (particularly the rotating and passive rotation joint) and implementing final refinements prompted by the recognition of previously overlooked errors which were assumed to be negligible. I made the required CAD models(except the slider) using the Autodesk Fusion360 software which helped me improve upon my CAD designing skills. I was also involved in researching the chordwise flexibility effects of the wing on its aerodynamics and this helped me learn a lot about the complex aerodynamics associated with flapping wings. Moreover I was actively involved in assisting with the assembly, experimentation and analysis of the obtained data. Throughout the project, I gained substantial knowledge about the process of engineering design

and discovered that collaborative teamwork is an effective means of overcoming the challenges inherent in the field.

3) Adithyan U S (21AE10049)- I researched extensively on how spanwise flexibility of the wing could affect the lift and thrust forces, and also about how passive rotation present in the wings of dragonfly helps in improving its efficiency. I drew different 2D projections of the model and its individual parts, and was able to identify different constraints and relations between dimensions of parts of the model, and thus helped in finding the dimensions of all components (including base, slider, gear system..). I researched about the working of the force sensor, wrote its code and measured the values from the force sensor (weight - lift) at different thicknesses of the wings. I helped in acquiring some materials by traveling outside campus in search of them.
Through this project, I was able to gain knowledge on how flexibility and passive rotation could affect the aerodynamics of in-flight motion and improve its efficiency. Engaging in dimensional analysis has significantly enhanced my logical and analytical skills, and allowed me to identify and rectify errors more effectively. Additionally, my knowledge has expanded in the realm of gear mechanisms, and I have gained practical experience in coding with Arduino and utilizing force sensors. This project has not only deepened my technical skills but has also contributed to my growth in teamwork, emphasizing the importance of collaborative efforts in achieving project goals.

4) Anfal S (21AE10003)-In the project, I played a crucial role in determining the dimensions of the body, showcasing my expertise in design. Additionally, I undertook the task of crafting the slider component using CAD software, thereby making a meaningful contribution to the overall functionality of the system. My involvement extended to the final assembly of the model, where my attention to detail ensured a seamless integration. Moreover, I actively participated in optimizing the performance of the force sensor, showcasing my commitment to enhancing the project's functionality.Engaging in this project provided me with invaluable hands-on experience on Softwares like Autodesk Fusion 360 for making CAD models and learned arduino as well.Engaging in this task further enriched my comprehension of the phenomena associated with the flexibility of flapping of wings. This comprehensive experience not only enriched my technical capabilities but also underscored the importance of interdisciplinary collaboration in achieving project goals, making it a meaningful learning journey.

5) Sagar K P (21AE30031)- I worked on determining the dimensions of the parts of the flapping wing model (the base , the passive rotation joint and the links to be specific). I determined how changing or fixing one parameter would affect the other parameters , for example how changing the length of the links and the width of the model would affect the angular range of motion of the wing , and how to accommodate for the sliding joint that connects the passive rotation joint to the slider being slightly displaced from the actual hinge of the wing. I was exposed to the nitty-gritties of actually designing a working hardware model from scratch. I also helped in putting together the model, by doing various tasks like gluing together parts , buying various components, getting the steel rod for the slider cut from the department workshop among many other small tasks. Even though I did not directly do the CAD modeling , I was extensively involved in the designing process so that I gained a decent knowledge as to how Fusion 360 software is to be used for CAD modeling. I also did some analysis of the data we collected and contributed to the brainstorming of various methods by which we could make sense of the data. Overall it was an intriguing and enriching experience for me that took me through the entire process of discovering, setting up and performing a meaningful experiment.

6) Allwin Johnjo Prince (21AE10002)- I contributed to a project by designing a simplified bevel gear mechanism essential for adjusting the phase difference in flapping. Additionally, I explored effective methods to convert gear rotation into flapping motion, utilizing interconnected links and a slide mechanism to transform rotational movement into vertical motion. I played a role in data collection, developing a code using CoolTerm software to gather information from the Arduino serial monitor and organize it into Excel for graph plotting. I also helped with assembly of the model. I also contributed in the compilation of information to make presentations.

   As a team overcoming the hurdles of material selection, mechanism design, and manufacturing processes taught us invaluable lessons in applied engineering and problem-solving and about the challenges of making a real time model. Working on data collection not only helped me to hone my programming skills but also underscored the importance of accurate data collection for analyzing and improving our mechanism. Throughout the project, I gained substantial knowledge about the process of engineering design by working on the design of bevel gear mechanism. Understanding how passive rotation contributes to the efficiency and stability of flight enhanced my knowledge on flapping wing aerodynamics.

7) Arjun Biju (21AE10007)- In the course of my involvement in the project, I conducted an extensive literature review focusing on theories elucidating the physics underlying the flexibility, lift, and drag forces associated with flapping wings. Additionally, I contributed to the assembly of the flapping wing by gluing together the wings and integrating them with the base model. I further worked in the meticulous testing of force sensors to quantify the lift forces acting on the wings. This involved subjecting the model to wind tunnel experiments within our laboratory. Subsequently, I collected and analyzed the experimental data, generating all the graphs for comprehensive interpretation. Through this project, I gained a profound understanding of concepts such as leading edge vortices and recognized the efficacy of collaborative efforts in achieving project objectives.