Thrust Analysis Of Box Wing Propeller

Group - 2

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■ Introduction:

In modern aircraft design, one of the most effective configurations for enhancing aerodynamic efficiency is the **box wing**. Box wings typically consist of a forward and an aft wing, joined by vertical endplates or winglets at the tips, creating a closed, continuous loop. This configuration The closed loop structure helps reduce the strength of wingtip vortices, which are the swirling air patterns that form at the wingtip and contribute significantly to induced drag. By minimizing these vortices, box wings achieve better lift-to-drag ratios compared to traditional wing designs, making them ideal for enhancing fuel efficiency and performance. Building on this principle, **box wing propellers** have been developed, offering greater efficiency than classical propellers of equivalent dimensions.

- **General Problem Description:** In an unstaggered box wing propeller configuration, the wake region of the upper blade interacts with the flow field of the lower blade. This interaction leads to a reduction in the pressure difference between the inlet and wake regions of the lower blade, consequently diminishing the overall thrust generated. To mitigate this issue and optimize aerodynamic performance, a staggered box wing propeller configuration is employed. By staggering the wings, the interaction between the flow fields of the upper and lower blades is significantly reduced, resulting in improved thrust and overall efficiency.
- **Motivation:-**
- **Increased Thrust:** By reducing wake interference, staggered configurations can generate higher thrust for a given power input.
- **Improved Propulsive Efficiency:** Minimizing energy losses due to wake interaction can lead to improved propulsive efficiency.
- **Research Question:** How can the thrust-to-power ratio of a staggered box wing propeller configuration be optimized for a given power input?
- **Objective:** To develop an aerodynamically optimized box wing propeller, which consumes less power for producing more thrust than the previous unstaggered propeller design.
- **Overview of the Presentation:** This presentation presents a comparative analysis of the thrust-to-power ratio for classical, staggered, and unstaggered box wing propeller configurations. Leveraging both computational fluid dynamics (CFD) simulations and experimental data, we will delve into the optimization of this ratio. A particular emphasis will be placed on the advantages and disadvantages of the innovative staggered design.

■ Design Methodology:-

- **Aerofoil Description:** For design of the propeller blades NACA 4412 aerofoil is used. The NACA 4412 is a four digit NACA series airfoil has several characteristics, including:

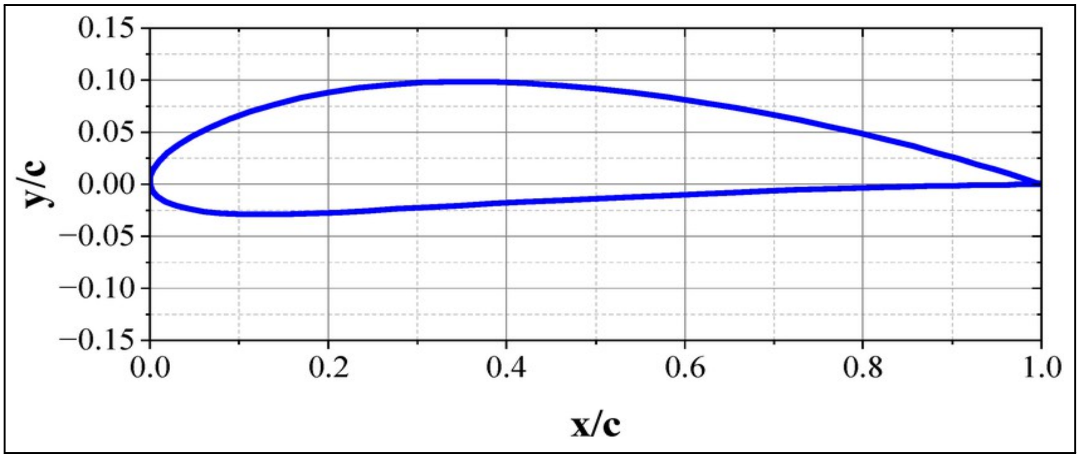


Fig 1: NACA 4412 Aerofoil profile.

✧ **Camber:** NACA 4412 has a maximum camber of 4% of chord located at 40% chord back from the leading edge and is 12% thick.

✧ **Low negative ground effect:** The nearly flat bottom surface of the NACA 4412 airfoil prevents the negative ground effect that occurs with extreme camber.

✧ **Low lift coefficients and high drag coefficients:** The NACA 4412 airfoil has low lift coefficients and relatively high drag coefficients.

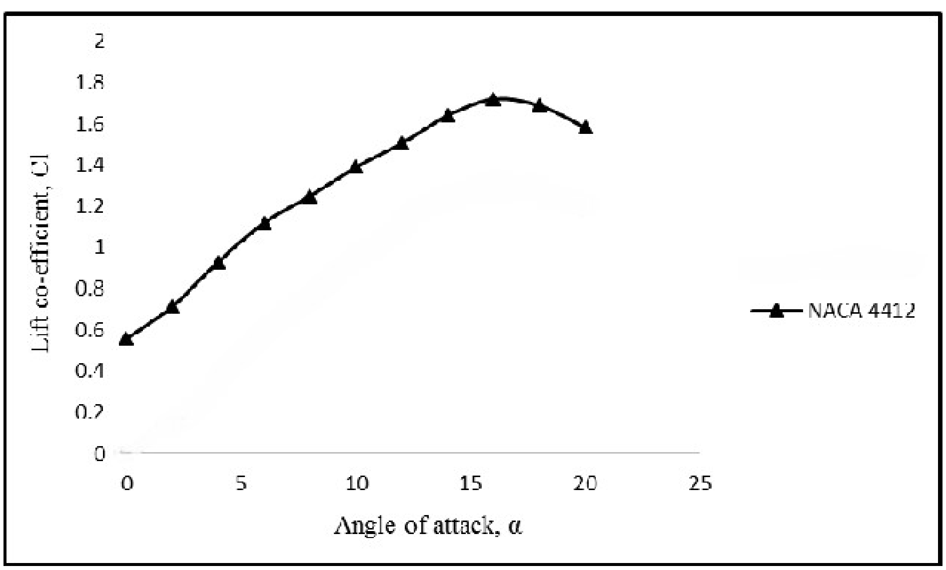


Fig 2: C VS α **Plot For NACA 4412.**

- **<u>Propeller Design</u>:** An initial design was developed using Fusion 360, informed by a thorough literature review. A novel approach was adopted by initiating the blade roots from the upper and lower flat surfaces of the hub, rather than the side curved surface, as is conventional. The NACA 4412 airfoil was selected as the cross-sectional profile for each blade. The final design was achieved through the strategic application of loft features and rail curves in Fusion 360.

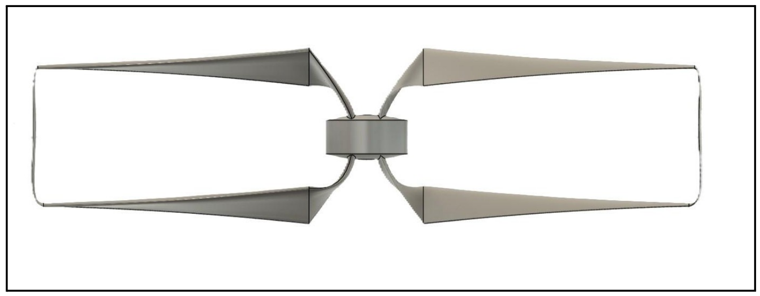



Fig 3: Initial Design.

- **<u>Propeller Description</u>:**
  - ✧ **Classical Propeller:** The classical propeller design was achieved by varying the angle of attack of the NACA 4412 airfoil cross-sections while maintaining the overall design methodology.

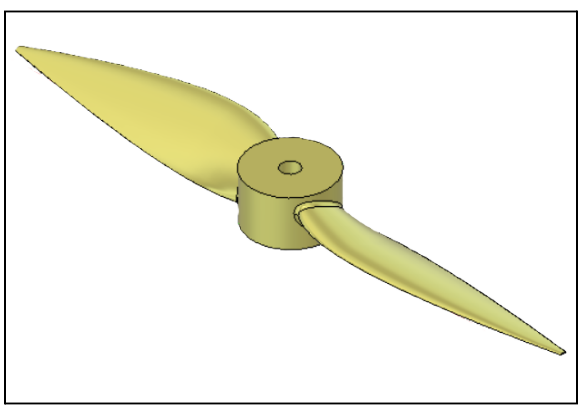
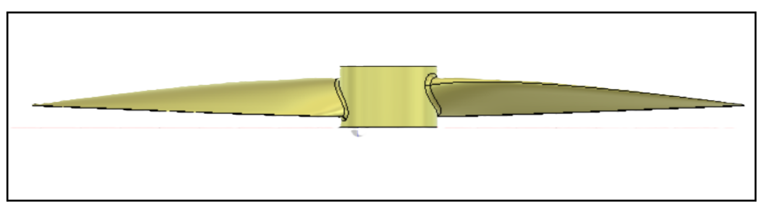
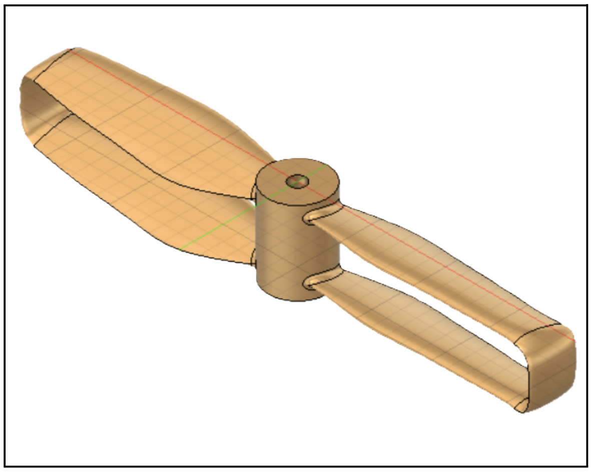



Fig 4: Classical propeller (CAD_Files).

✧ **Unstaggered Box Wing Propeller:** For the unstaggered box wing propeller, we systematically varied the angle of attack of the airfoil cross-sections while maintaining a constant vertical distance and zero stagger angle. Winglets were added to mitigate tip vortex losses.



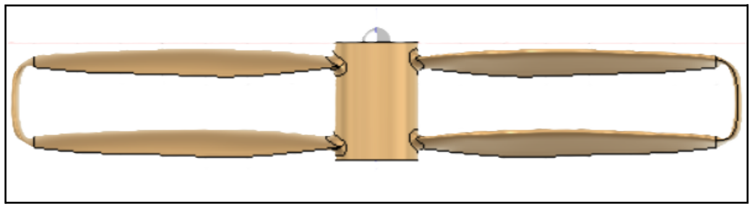
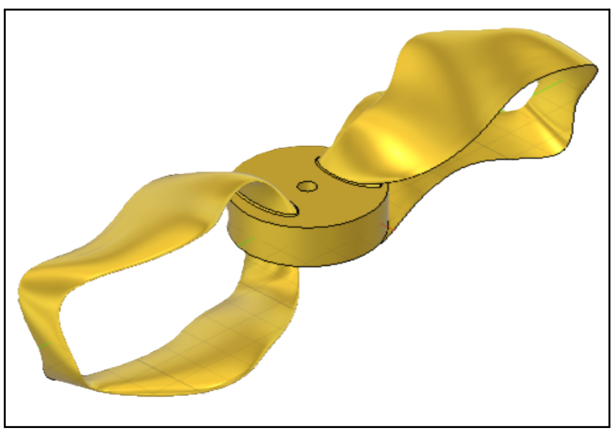


Fig 5: Unstaggered Box Wing Propeller (CAD_files).

✧ **Staggered Box Wing Propeller:** For the unstaggered box wing propeller, the angle of attack of the airfoil cross-section was varied for both blades, while the vertical distance between them was adjusted for each section. To reduce wingtip vortices, winglets with elliptical airfoil profiles were incorporated.



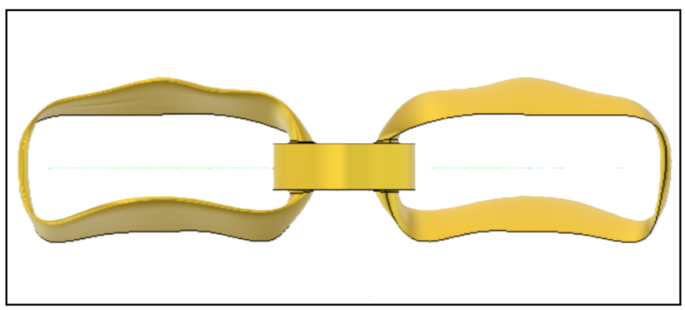


Fig 6: Staggered Box Wing propeller (CAD_Files).

Table 1: Design parameters.

Parameters	Classical Propeller	Unstaggered Box Wing Propeller	Staggered Box Wing Propeller
Propeller Blade Diameter (cm)	18 cm		
Propeller Hub Diameter (mm)	25 mm	20 mm	40 mm
Shaft Diameter of the motor	5 mm		
Shaft Length of the motor	4 cm		

- **<u>Manufacturing Technique</u>:** 3D Printing
- **<u>Materials for 3D Print</u>:** PETG, ABS
- **<u>Experiment</u>:-**
  - ✧ **Appratus:** 12 V DC Power Supply, A2212 BLDC Motor, Electronic Speed Controller, Servo Tester, Digital Voltmeter (0-100V) and Ammeter (10A)-LED Display, Connecting Wires, Weighing Machine.
  - ✧ **Experimental Setup:-**

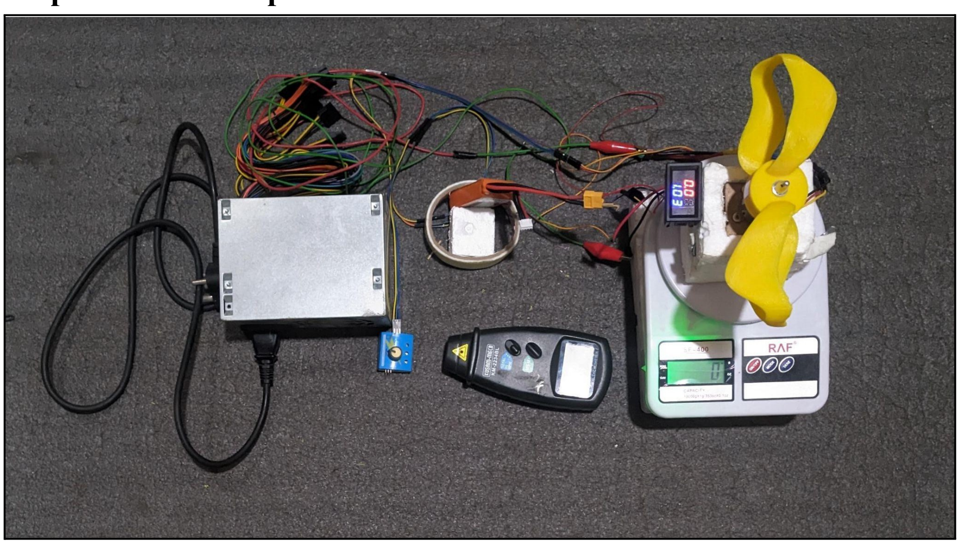


Fig 7: Experimental Setup.

- **<u>CFD Description</u>:**

The CFD simulations of the propellers involved several critical steps to ensure accurate and comprehensive analysis. Initially, detailed 3D models of the propellers were created using CAD software. These models were imported into CFD software to generate a high-quality mesh, discretizing the computational domain into smaller elements for numerical analysis. The Moving Reference Frame (MRF) approach was utilized to simulate the relative motion between the rotating propeller and the stationary fluid, capturing the complex interaction between the blades and the fluid accurately. CFD solvers were employed to solve the Navier-Stokes equations, which govern the fluid flow, thereby calculating essential flow properties and performance metrics such as thrust, drag, and pressure coefficients. Boundary conditions were defined with a velocity inlet, a pressure outlet, and a no-slip wall condition on the propeller surface to account for frictional effects. Post-processing techniques were then used to interpret the results, providing valuable insights into the flow physics and aerodynamic performance of the propellers. Key metrics like thrust and drag were analyzed, and pressure coefficients were visualized to understand the aerodynamic characteristics of the different propeller designs.

■ Results:-

● CFD Results:

✧ **Classical propeller ([Fluent_Files]):-**

a. Thrust Value (At 6317 rpm):

Zone	Forces [N] Pressure	Viscous	Total	Coefficients Pressure
propeller	1.1970132	-0.0070798822	1.1899333	1.9543072
Net	1.1970132	-0.0070798822	1.1899333	1.9543072

b. Contours:-

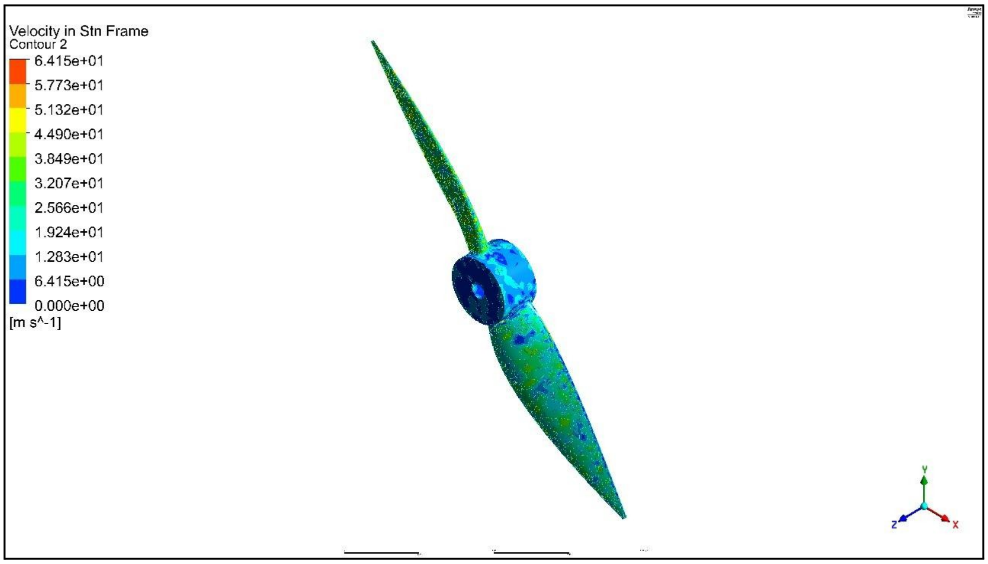


Fig 8: Velocity Contour (Classical propeller).

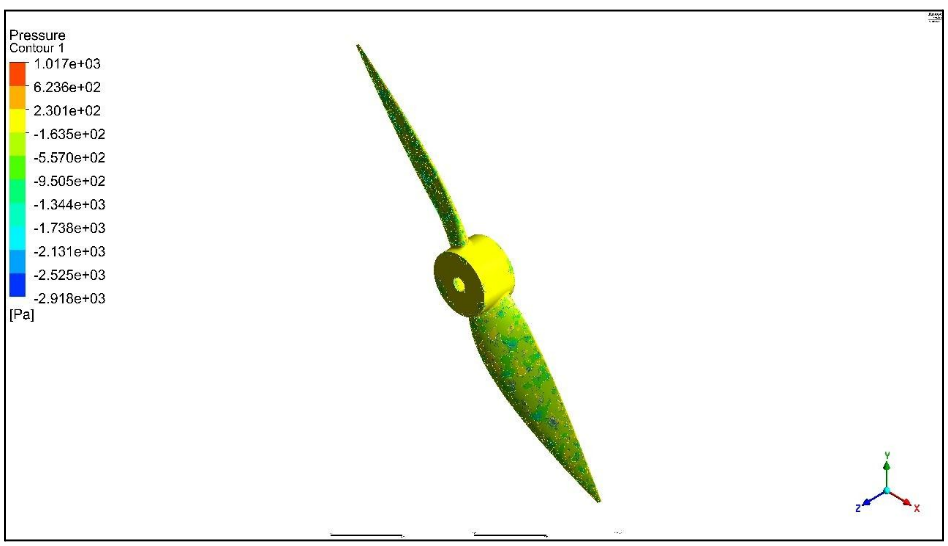


Fig 9: Pressure contour (Classical propeller).

✧ **Unstaggered Box Wing Propeller (Fluent_files):-**

A. Thrust Value (At 6709 rpm):-

```
Calculation complete.

                                    Force                   [N]
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                               propeller          1.5529234
```

B. Contours:-

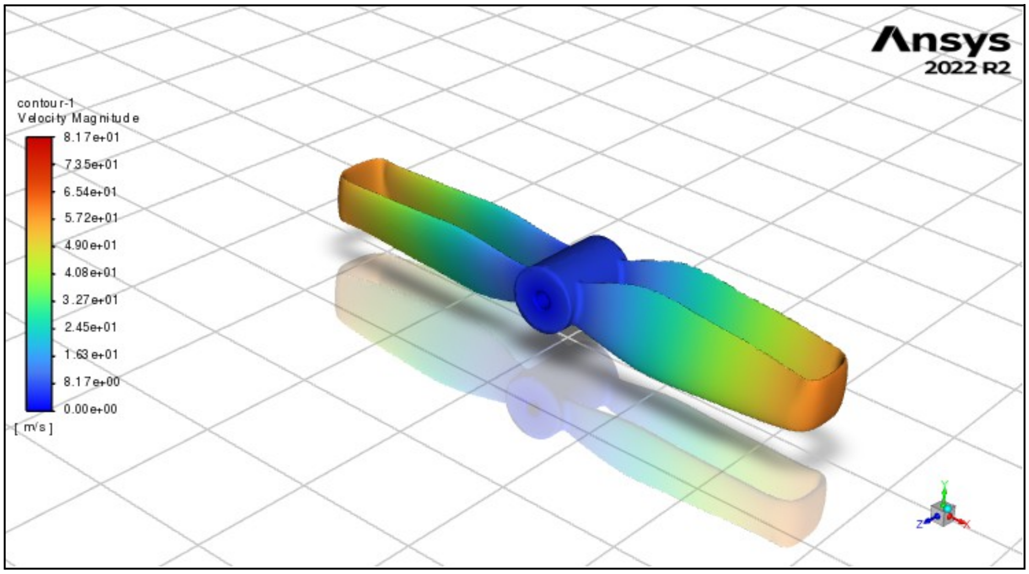

Fig 10: Velocity Contour (Unstaggered Box Wing propeller).

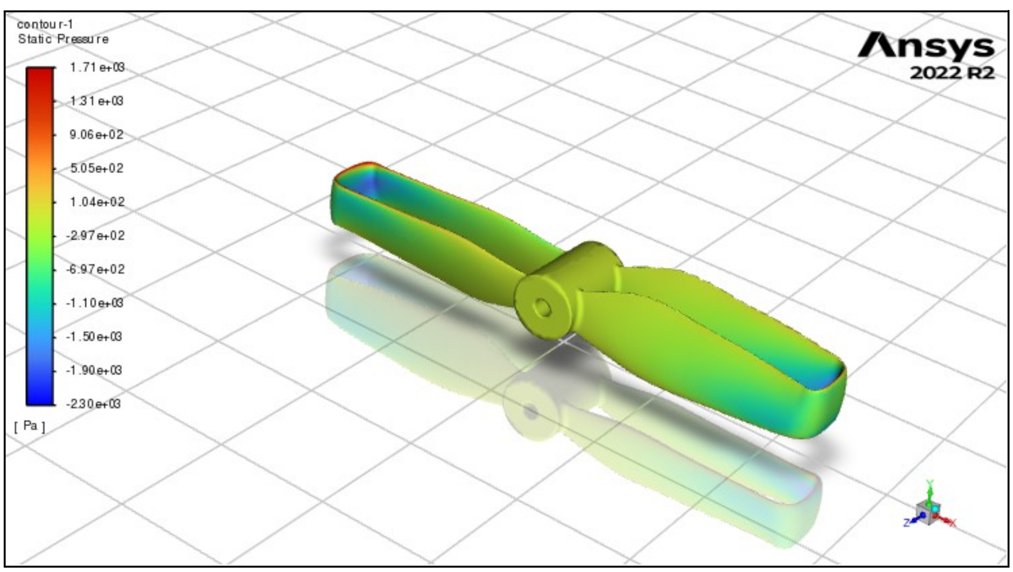

Fig 11: Pressure Contour (Unstaggered Box Wing Propeller).

✧ **Staggered Box Wing Propeller (Fluent_files):-**

A. Thrust value(At 4508 rpm):-

```
Calculation complete.
                              Force                  [N]
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                         propeller            1.778036
```

B. Contours:-

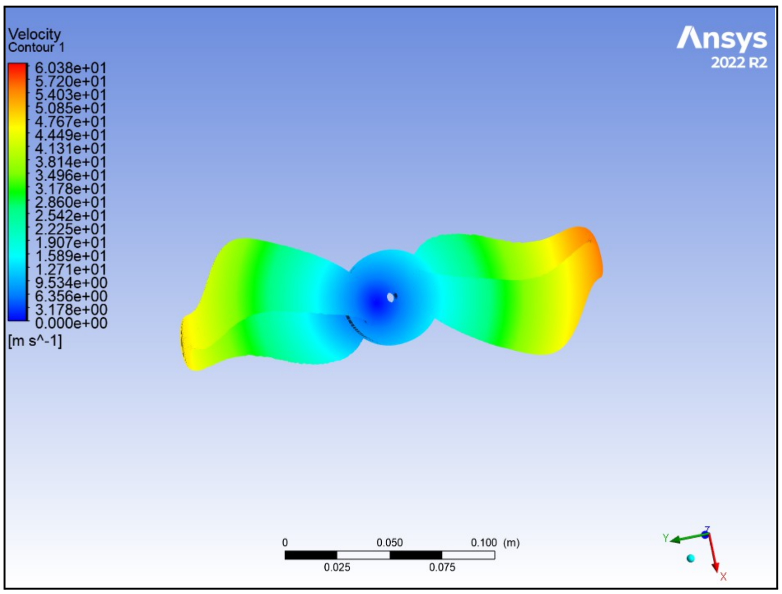

Fig 12: Velocity Contour (Staggered Box Wing Propeller).

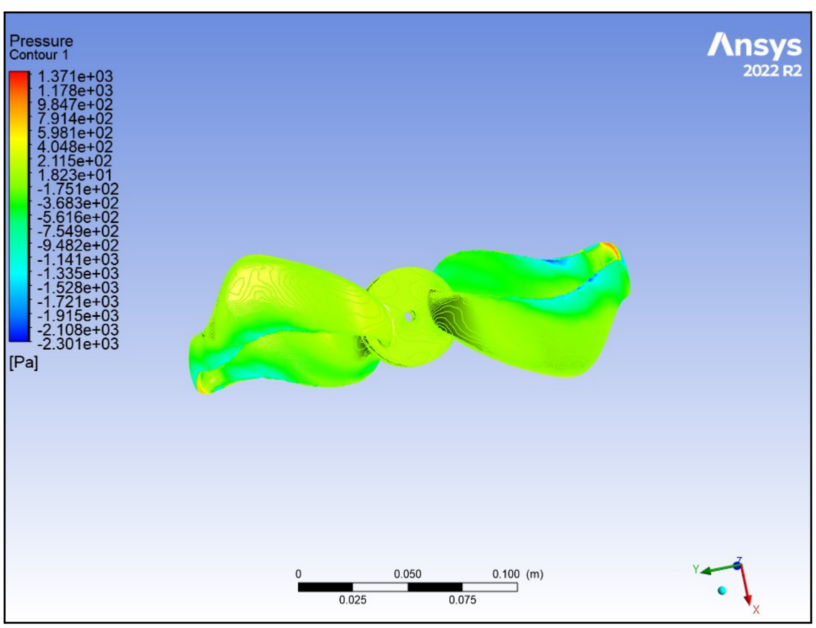

Fig 13: Pressure Contour (Staggered Box Wing Propeller).

- ## Experimental Results:

✧ Classical propeller (Video):

Table 2: Experimental data for Classical propeller.

Classical propeller				
V	A	Power (Watt)	RPM	Thrust (gm-wt)
11.5	2.07	23.805	3690	40
11.4	2.38	27.132	4214	51
11.1	3.04	33.744	4968	71
10.8	3.75	40.5	5606	88
10.5	4.39	46.095	6060	101
10.3	4.69	48.307	6176	108
10	5.34	53.4	6540	116
10.2	5.5	56.1	6540	112
10.2	5.03	51.306	6317	114

✧ Unsatggered Box Wing Propeller (Video):

Table 3: Experimental data for Unstaggered Box Wing propeller.

Unstaggered Box Wing Propeller				
V	A	Power (Watt)	(RPM)	Thrust (gm-wt)
11.9	1.29	15.351	1619	11
11.8	1.44	16.992	2300	20
11.8	1.5	17.7	2831	30
11.6	1.8	20.88	3322	42
11.5	1.91	21.965	3536	48
11.5	2.14	24.61	3941	58
11.4	2.27	25.878	4139	64
11.2	2.56	28.672	4534	76
11	2.98	32.78	5000	93
10.8	3.64	39.312	5583	114
10.5	4.1	43.05	5906	126
10.2	4.81	49.062	6307	144
9.6	6.29	60.384	6709	166
10	5.18	51.8	6405	159

✧ Staggered Box Wing Propeller (Video):

Table 4: Experimental data for Staggered Box Wing propeller.

Staggered Box Wing Propeller				
V	A	Power (Watt)	(RPM)	Thrust (gm-wt)
11.9	1.29	15.351	1173	13
11.8	1.44	16.992	1690	24
11.8	1.53	18.054	1891	32
11.6	1.74	20.184	2242	45
11.6	1.87	21.692	2454	53
11.6	1.88	21.808	2451	51
11.5	2.06	23.69	2660	61
11.4	2.24	25.536	2929	70
11.4	2.48	28.272	3134	80
11.1	2.92	32.412	3473	102
11.1	3.15	34.965	3588	111
10.9	3.49	38.041	3808	124
10.6	3.95	41.87	4080	134
10.5	4.28	44.94	4206	145
10.1	5.14	51.914	4368	167
10.2	4.24	43.248	4388	158
10.2	5.08	51.816	4445	164
9.36	6	56.16	4508	189

◆ Comparison between CFD and Experimental Values:-

Table 5: Thrust of different models.

Parameters	Propeller	CFD Results (gm-wt)	Experimental Results (gm-wt)
Maximum Thrust	Classical	121	116
	Unstaggered Box Wing	160	166
	Staggered Box Wing	178	189

◆ Plots:-

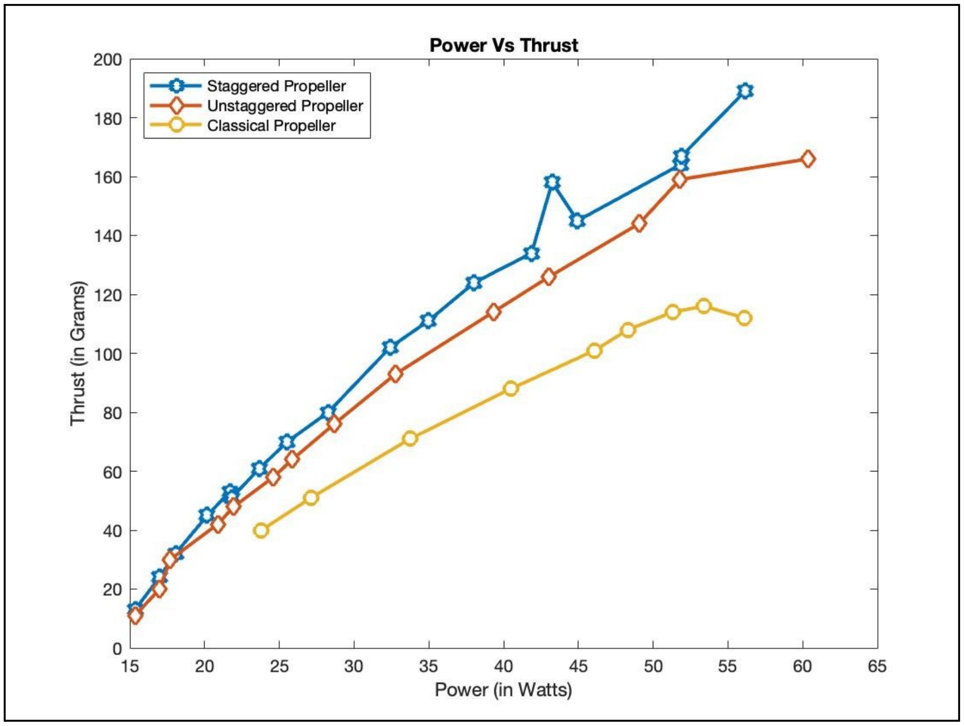

Fig 14: Power (Watt) Vs Thrust (gm) plot.

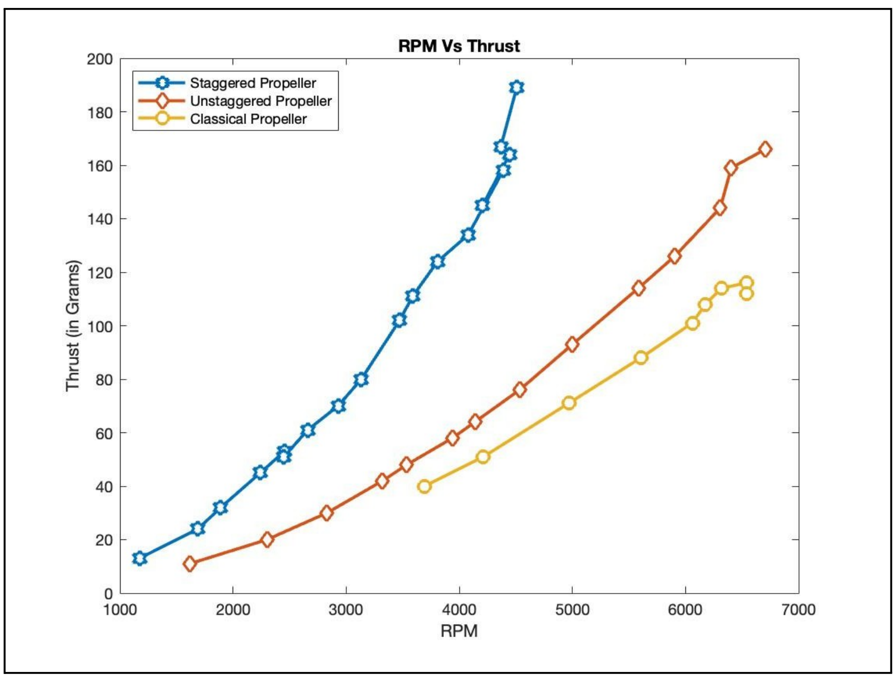

Fig 15: RPM VS Thrust (gm-wt) plot.

■ Discussion:

This design project investigates the aerodynamic performance of staggered and unstaggered box wing propeller configurations. The study involves a combination of CFD simulations and experimental analysis to assess the impact of design parameters on thrust, power, and efficiency.

✧ Key Findings:-

1. **Wake Interference:** Unstaggered configurations exhibit significant wake interference between the upper and lower blades, leading to reduced thrust and increased power consumption. The wake vortices generated by the upper blade interact with the lower blade, increasing drag and reducing the overall efficiency of the propeller. This interference is particularly pronounced at higher angles of attack and higher rotational speeds.
2. **Staggered Configuration Advantages:** Staggered configurations effectively reduces wake interference, resulting in improved thrust-to-power ratios and enhanced aerodynamic efficiency.
3. **Design Parameter Influence:** The angle of attack of the airfoil cross-sections and the vertical distance between the blades significantly impact the performance of both staggered and unstaggered configurations.
    a. **Angle of Attack:** The angle of attack determines the amount of lift generated by the airfoil. By adjusting the angle of attack, the thrust and efficiency of the propeller can be optimized.
    b. **Vertical Distance:** The vertical distance between the blades influences the interaction between the wake vortices generated by each blade. In staggered configurations, proper spacing can reduce wake interference and improve overall performance.
4. **Effects of Winglets:** Winglets are small vertical extensions at wingtips that reduce the formation and strength of wingtip vortices. These vortices create drag and decrease efficiency. Winglets alter vortex formation, redirect airflow, and effectively increase wingspan, leading to reduced drag and improved aerodynamic efficiency. The addition of winglets to the staggered and unstaggered configuration helped reduce wingtip vortices and improved overall efficiency quite significantly.
5. **Structural Stability:** While our initial design demonstrates strong structural stability at lower RPMs (below 4600 RPM), concerns arise regarding the potential failure of the joint between the blades and the winglets at higher RPMs. The thin nature of the joint may render it susceptible to high shear stresses, compromising the overall structural integrity of the propeller.

■ Conclusion:

This project highlights the superior aerodynamic performance and efficiency of staggered box wing configurations compared to their unstaggered counterparts. While classical propellers offer simplicity, their efficiency is limited by higher induced drag. Unstaggered box wing propellers show improvements by reducing wingtip vortices but are hindered by aerodynamic interference between forward and aft blades. The staggered box wing propeller emerged as the most efficient design, achieving the highest thrust-to-power ratio by minimizing interference, optimizing wake recovery, and enhancing flow distribution. This study highlights the potential of staggered configurations to revolutionize propeller technology, paving the way for more sustainable and high-performance aviation systems. Some questions are still unsolved which will be taken care of in the future research -

a. **Noise Reduction:** Investigate noise reduction techniques, such as blade shape optimization and active noise control.
b. **Unsteady Flow Effects:** Consider the impact of unsteady flow phenomena, such as dynamic stall, on propeller performance.
c. **Alternative Configurations:** Explore novel box wing configurations, such as V-shaped or W-shaped arrangements, to further enhance performance.

■ Individual Learning Statements:

❖ Adeeba Khan (22AE10001)

In this design model project, I gained valuable experience in propeller design, focusing on factors such as size, shape, material, and operating conditions. I also learned how to evaluate propeller performance through experimental analysis, which deepened my understanding of using simulations to predict real-world performance. Additionally, I contributed to ensuring the stability of the experimental setup by suggesting improvements to the electrical connections, which played a crucial role in the experiment's success.This project also helped me develop essential soft skills like teamwork and communication, as I collaborated with my team to address design challenges and present our findings. Working together taught me how to effectively share ideas, listen to others, and make informed group decisions.

❖ Aditya Raj Shit (22AE10002)

In this project, I learned the process of propeller design, considering factors like size, shape, material, and operating conditions. I also explored performance assessment through CFD simulations and experimental analysis, gaining insight into how simulations predict real-world performance.

Also via experiment we learned about the importance of stress analysis, so as to stay within safe limits of operation. We also came to know about another device - tachometer and it's use to measure the rpm of the propeller. We also appreciated the fact that measuring downward thrust is better because in that case reading of the weighing machine will increase as it is made to measure normal force while in the other case the normal force may even become zero and go beyond it, making our estimation of thrust a bit difficult.

Additionally, I developed important soft skills like teamwork and communication, as I had to collaborate with my team to solve design challenges and present our findings. Working together helped me learn how to share ideas, listen to others, and make decisions as a group.

❖ Arghadeep Das (22AE10003)

This design project provided a valuable opportunity to apply theoretical knowledge to practical implementation. I significantly contributed to the CAD modeling aspect of the project, developing intricate 3D models of the box wing propeller configuration. Additionally, I actively participated in the experimental setup, gaining hands-on experience in instrumentation and data acquisition. While the project presented challenges, such as overcoming obstacles during CFD analysis and adhering to tight timelines, it fostered resilience and problem-solving skills. The collaborative nature of the project enabled me to learn from my peers and contribute to a collective effort. Ultimately, this experience has enhanced my technical abilities, deepened my understanding of aerodynamic principles, and instilled a passion for innovation.

❖ Arghyadip Mondal (22AE10004)

The project provided a meaningful opportunity to combine conceptual knowledge with real-world application, significantly advancing both my technical and interpersonal skills. Through iterative processes for improved precision, I gained expertise in SolidWorks and ANSYS Fluent, particularly while developing detailed 3D models of the box-wing propeller system. I also played an active role in setting up experiments, acquiring practical experience in equipment handling and data collection, and further honing my hands-on abilities. Working collaboratively within a group of 10 team members enhanced my communication and coordination skills, enabling me to contribute effectively to shared goals. Despite hurdles such as addressing complexities in CFD simulations and meeting strict deadlines, the experience boosted my adaptability and critical thinking capabilities. Ultimately, this project expanded my knowledge of aerodynamic concepts, refined my practical skills, and fueled my enthusiasm for creativity and teamwork.

❖ Ishaan Sharma (22AE100013)

Through this project, I learnt the basic principles and concepts involved in propeller design through literature review and analyzing existing designs. I got the opportunity to enhance my CAD skills, in order to design a propeller which would be both aerodynamically efficient as well as structurally strong to withstand high rotational speeds. I also learned how to test and analyze a propeller's performance using Computational Fluid Dynamics, through enclosures and rotating wall boundary conditions in ANSYS Fluent. Other than that, this was my first experience of working in such a large team, and so I learnt how to efficiently divide work among each other, collaborate and discuss with others to gain better insights.

❖ Kalyani Kalavakunta (22AE10017)

Through this design project, we had the opportunity to design and test a staggered box wing propeller. My role involved CAD modeling, assisting experiments, and analyzing data. During the project, we faced several challenges. The propeller model broke multiple times during testing, necessitating several reprints. Each breakage allowed us to refine the design and materials, resulting in a more robust final model. We also discovered that the hub and extension were unsuitable, which required redesigning and close collaboration with team members to implement better solutions. Despite these difficulties, we successfully conducted the experiments, obtained thrust data, and compared the results with a classical propeller and an unstaggered box wing propeller. This project significantly enhanced my understanding of propeller aerodynamics and improved my skills in CAD modeling, experimental setup, data collection, and result analysis. It also strengthened my ability to work effectively in a team and approach problems systematically and in a structured manner.

❖ Roshan Bajaj (22AE10033)

During the project, I was primarily involved in CAD modelling, CFD analysis, experimental setup and data collection. I learnt about the basics of propeller designs and the importance of various parameters. I contributed to developing the staggered propeller's CAD model, enhancing my proficiency in SolidWorks. I referred to tutorials and documentation to improve my skills and ensure an accurate and efficient design. I assisted in performing CFD simulations, learning how to set up boundary conditions, mesh the geometry, and analyse results using ANSYS Fluent. This process deepened my understanding of fluid flow and aerodynamic performance analysis.

This project significantly enhanced my time management and communication skills. Collaborating with my team members and learning from their expertise was a rewarding experience.One final point I would like to highlight is the numerous challenges we faced during the project. We encountered several setbacks, including issues with the experimental setup, motor failures, and damage to the model on four to five occasions. Initially, the propeller did not produce the desired thrust, which required us to revisit and refine our CAD model. This iterative process involved redesigning the propeller, performing additional CFD analyses, reprinting the model, and conducting further experiments. Despite these obstacles, each failure taught us valuable lessons, and overcoming them was a rewarding experience that contributed significantly to the success of the project.

❖ Subhro Halder (22AE10039)

Throughout the project, I learnt about the design of propellers and the importance of various parameters. During the project, I was also Involved in the CAD design part which improved my Design Skill. I learnt various optimization techniques which helped me throughout the project. I learnt various Computational methods to test and run the simulation for propellers in Ansys Fluent. I am thankful for the valuable knowledge and insights I gained throughout this project, which significantly enhanced my understanding and skills. We faced many difficulties throughout the project but finally we overcame all of this, and all the team members have been incredibly supportive and helpful throughout this project.

❖ Milan Kumar (22AE30020)

This design project provided me with a great opportunity to work with a team. In our project we did cad modeling of propellers and got a good insight in optimising the propeller design. We faced many difficulties from printing to structure failure of the model and that gave me the opportunity to learn managing things and to tackle problems. We modified our model day by day by learning from our mistakes. We learned the importance of structural strength of the model and how it is very important to do the experiment with safety and proper setups. This project helped me in improving communication skills and helped me in getting a deep insight of group work. I learnt lots of things from my teammates and their expertise. The issues we faced during the experiments gave us nice lessons and it helped our model to build more and more efficiently. It helped me in my overall development as a team, but my experimental skills got enhanced specially.

- ### Satvik Jaiswal (22AE30024)

This project taught me how to turn an idea into a working model by starting with CAD design, then simulations to get a rough idea of what would work, then improving the design based on the simulations, and finally 3D printing the model. After that, I contributed to designing the necessary circuits and did some tests, which led to some promising results. Through this iterative process, I got to learn how to optimize the design based upon high drag values and model failures like this to get a significant result like this.

I gained valuable insights into propeller physics by exploring various literature on innovative designs such as toroidal propellers, contra-rotating propellers, and propellers with tubercle designs. This research deepened my understanding and helped us select a box wing propeller as a design that was both innovative and practical.

This project also helped me improve my skills in CAD modeling, running simulations with ANSYS Fluent, and understanding how things work in real-world applications. Redesigning the hub and extensions was a challenge that required teamwork, which improved my problem-solving and collaboration skills. It also gave me a better understanding of how theory and practice come together, especially when using experiments to fine-tune propeller performance.

Overall, this project was a great learning experience. It taught me how to collaborate effectively, think more analytically, and use technology to turn ideas into successful outcomes.

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