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Design and Analysis of Magnus Effect Mechanism on Wing for UAV Applications

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Abstract: The Magnus effect, originally observed as the deflection of a spinning ball, has significant implications for aerodynamic phenomena when applied to airfoil surfaces. This research investigates the Magnus effect over a wing through computational methods. This paper presents the application and impact of magnus effect on the rotating upper surface of the wing. NACA 4412 airfoil is being considered for the analysis and preliminary results are presented in this paper. Analysis is carried out at different angles of attack to study the variation of aerodynamic characteristics. This paper aims at delaying the stall for an aircraft and also to study the lift and drag over the wing with rotating upper surface. Airfoil data was imported from airfoiltools.com and analysis is carried out using fluent solver. Results indicate that the Magnus effect alters lift generation and induces significant changes in drag, influenced by factors such as airfoil geometry and spin direction. Insights from this study contribute to advancing the understanding of unconventional aerodynamic mechanisms and have potential applications in the design of specialized aircraft.

Keywords: Magnus effect**,** NACA, airfoil, lift, drag, aerodynamic mechanism.

1. Introduction

The Magnus effect is a phenomenon that occurs when a spinning object moves through a fluid,such as air or water. The spinning object creates a difference in pressure on its opposite sides,resulting in a force perpendicular to the direction of motion. This force can cause the object todeviate from its original path, such as a football curving in the air or a cricket ball swinging inthe air. In the beginning of the 20th century, it was understood that the rotation of the cylinderproduces a circulation of the air close to the skin of the cylinder and furthermore a lift force. The idea arose that a rough surface could improve the circulation around the cylinder and therefore enhance the Magnus effect, providing even more lift force than a smooth surface. Anapplication of a rotating cylinder in aeronautics for boundary layer control can solely indicateaerodynamics differentiation between a conventional wing and a rotating cylinder as a wing. The Magnus effect can also be applied to wing surfaces with rotating surfaces, such as cylindersor spheres. The rotating surfaces can generate lift or downforce by altering the airflow aroundthe wing. This can improve the aerodynamic performance of the wing, such as increasing the lift-to-drag ratio, delaying the stall, or enabling vertical take-off and landing. [1,2] The Magnus effect works by altering the airflow around the spinning object. The object dragssome of the fluid along with it due to friction. This creates a region of higher speed and lowerpressure on one side of the object, and a region of lower speed and higher pressure on the otherside. The pressure difference generates a lift force that pushes the object towards the lower pressure side. The direction and magnitude of the force depend on the direction and speed of the spin, as well as the shape and size of the object. The Magnus effect has many applications. [3,4,5]

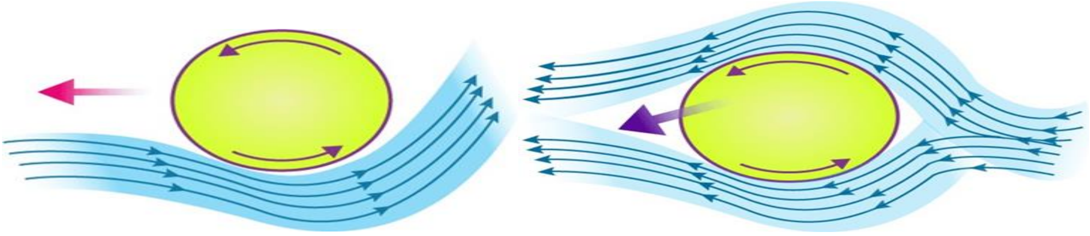
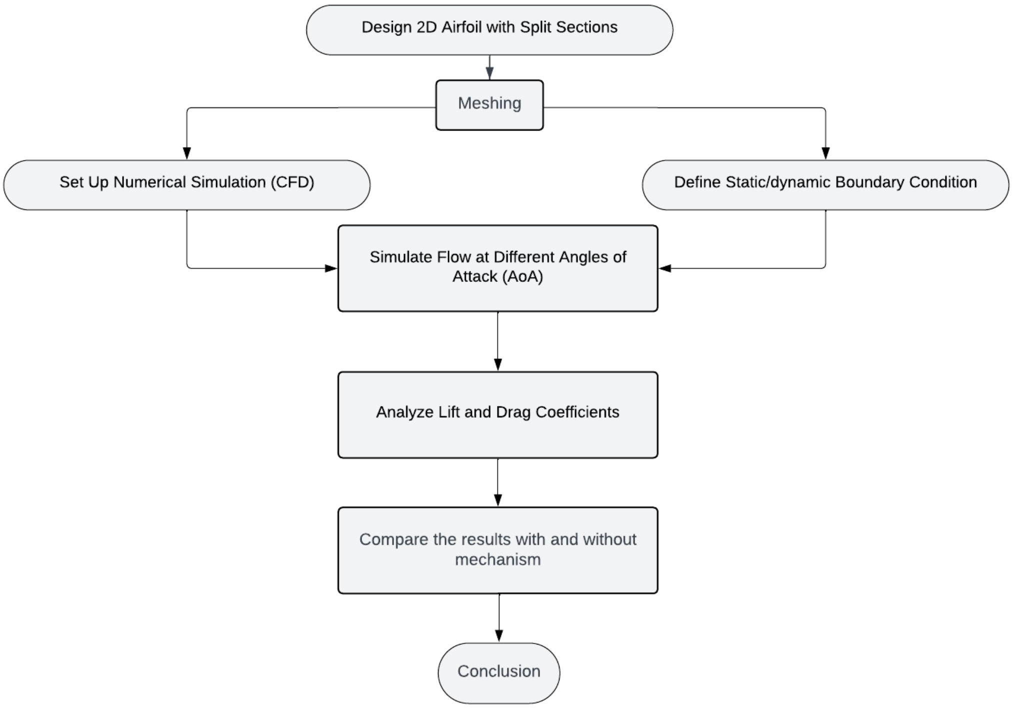


Fig 1 Magnus effect

in sports, such as football, golf, cricket, tennis, baseball, and others. By spinning the ball in different ways, players can control the trajectory and movement of the ball. For example, a football player can bend a ball around a wall by kicking it with an anticlockwise spin, which makes the ball curve to the left. A cricket bowler can make the ball swing in the air by rotatingthe seam of the ball, which creates an uneven airflow around the ball.

2. Methodology



3. Design:

3.1 Wing Concept:

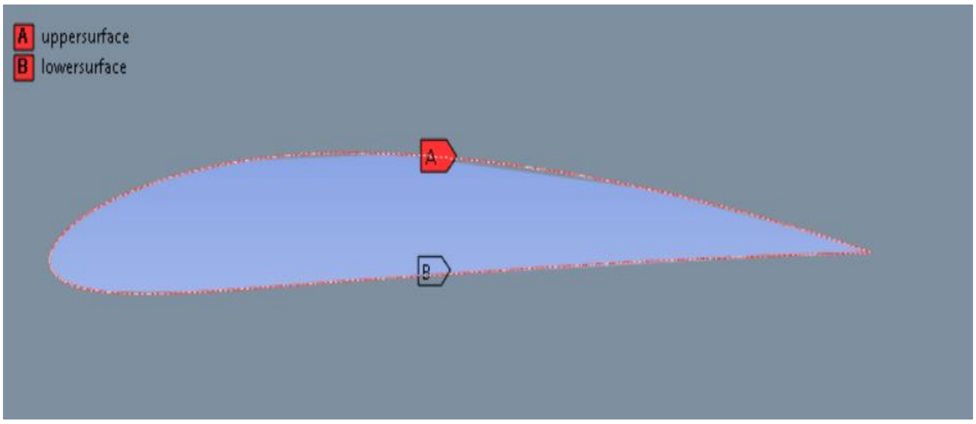


Fig 2 NACA 4412 airfoil

As shown in fig 2 there will be a 2D split geometry of chord 100mm utilized for numerical solutions considering the comparative study between magnus effect wing concept and static airfoil. In magnus effect the bottom surface is static and upper surface is moving at speed of 50 rpm considering the drive shaft shown in design.[1][2][3]

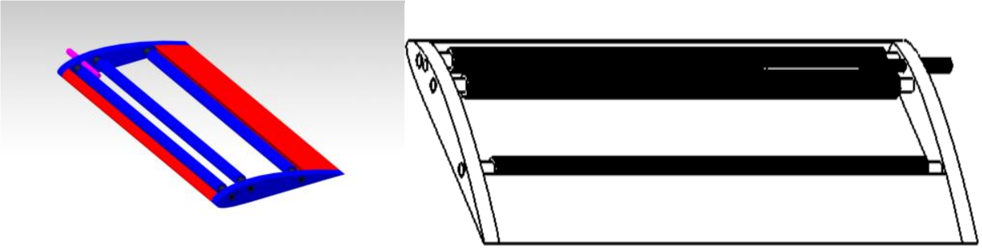


Fig 3 Wing internal drive mechanism for the magnus effect setup.

Wing includes belt mechanism supported by drive shaft utilized to rotate upper surface in controlled manner by controlling the mechanical input by dc motor.[7,8,9]

3.2 Mesh independence test:

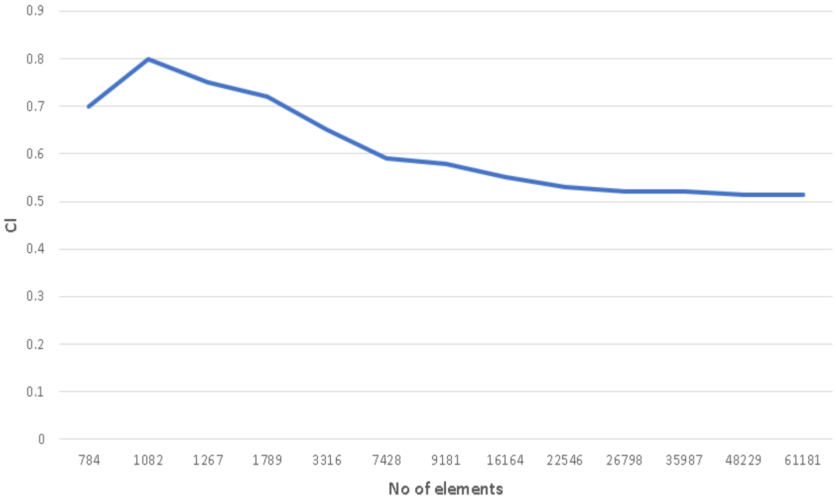
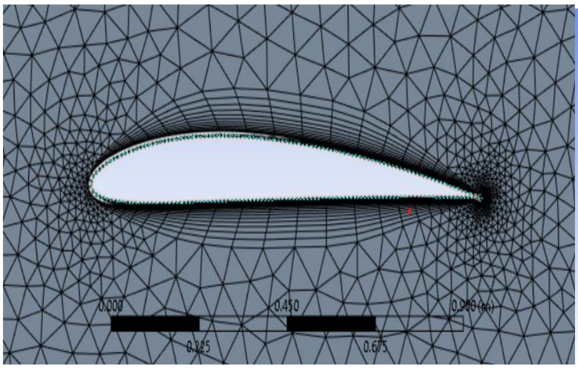


Fig 4 Mesh independence test

This is the way of verifying if the solution is independent of the grid or not to generate a grid with more cells to distinguish the solutions of the two models. Refining the grid and examiningfor lift coefficient we find that for about 61112 cells, the values don't vary substantially affecting the output. This is chosen to improve the accuracy and diminish computation time.[19]

Meshing:



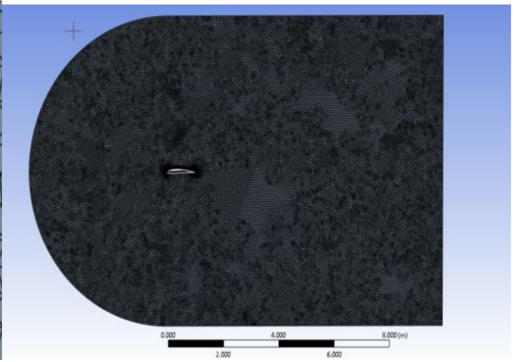


Fig 5 Meshing around airfoil **Fig 6 Meshed domain**

Above fig 5 showcases the mesh pattern utilized for the numerical solution setup in Ansys Fluent generated utilizing triangular elements with boundary layer setup adding inflation and smooth transition parameters. [21,22]

Comparative Study:

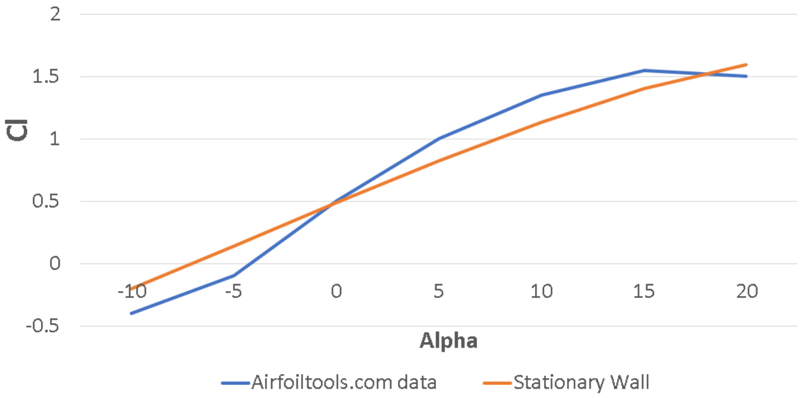


Fig 7 Comparative study

This is the comparison between the fluent solver results and Airfoil tools data which showcases the accuracy of the used tool.

Airfoiltools.com data	Stationary Wall	Alpha	Error
-0.4	-0.2	-10	10
-0.035	0.14	-5	-12.4
0.5	0.48	0	0.2
1	0.82	5	2.1
1.35	1.13	10	1.9
1.55	1.4	15	1
1.5	1.59	20	-0.5

Table 1. Comparison study of Cl value with error estimation

To verify the software, results from the Airfoiltools.com and obtained results are compared.The error obtained should be within 15% tolerance. This ensures that the results obtained fromthe software and the methodologies are accurate and positive for the project. Fig 7 and the table 1 gives an insight into the validation that was conducted on the NACA 4412 airfoil. [19,22]

4. Numerical Solutions:

Obtained results from the fluent solver is been comparatively plotted for moving and non-moving wall condition, these plots showcase the values of Cl, Cd, Cm and Cl/Cd with respect to angle of attack ‘alpha’.Below fig shows the numerical result comparison between moving wall i.e., magnus effect model and static model for CFD analysis carried out at various angle of attack with inlet flow velocity of 15 m/s.

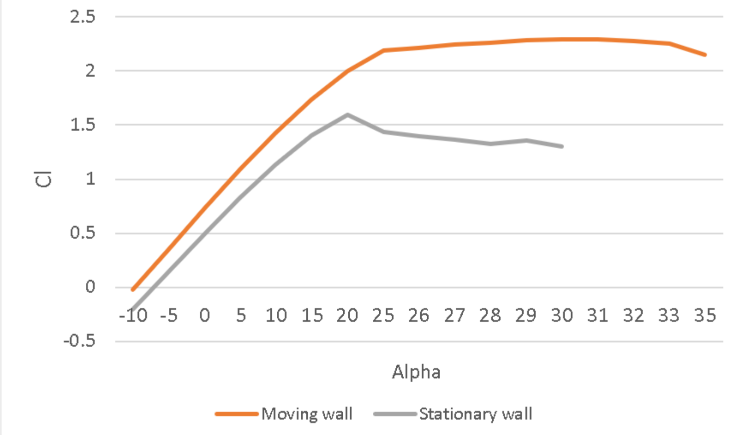


Fig 8 Cl vs α curve

Fig 8 shows that the Cl values remains linearly increasing till 20º for non-moving wall and 25º for moving wall condition, the difference is positively increasing for moving wall condition. The stall is also delayed from 20º to 31º for moving wall condition avoiding early flow separation.

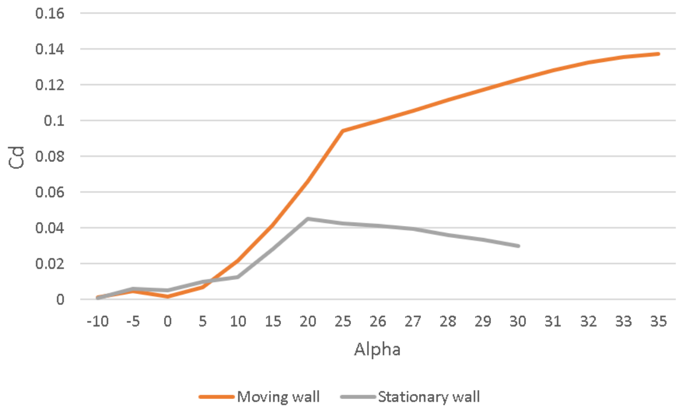


Fig 9 Cd vs α curve

Cd value remains lower in the range of -5º to 5º for moving wall condition which makes it more efficient in this range to operate, after 20º angle of attack the Cd significantly get increased after 10º angle of attack. Considering the Cd value after 25º makes a drastic difference which makes it inefficient to apply in the same range.

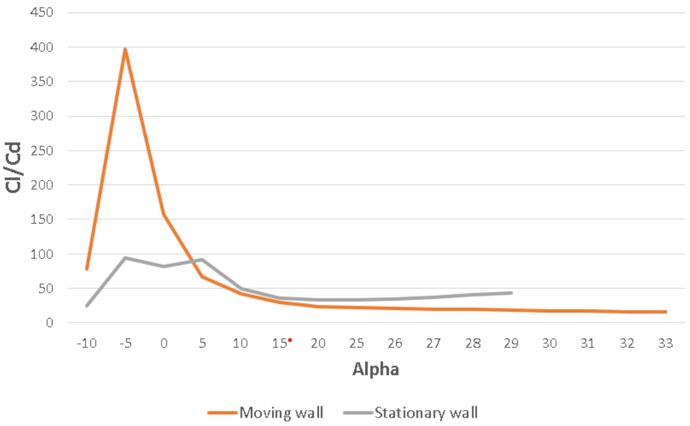


Fig 10 Cl/Cd vs α curve

The Aerodynamic efficiency spikes on 400 at -5º and remains more comparatively in moving wall condition till 4º Angle of Attack. Remains same till 15º AoA.

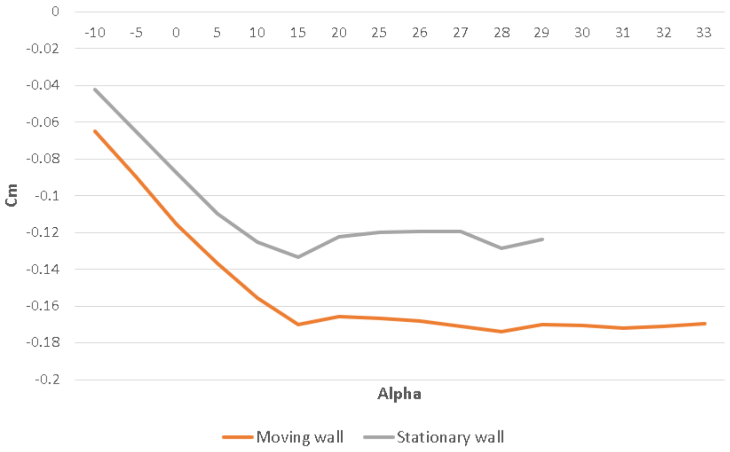


Fig 11 Cm vs α curve

Cm value remains constantly lower in moving wall with negative slope which denotes the longitudinal stability of the particular setup. After 15^{o} AoA the Cm value almost remains same for both case.

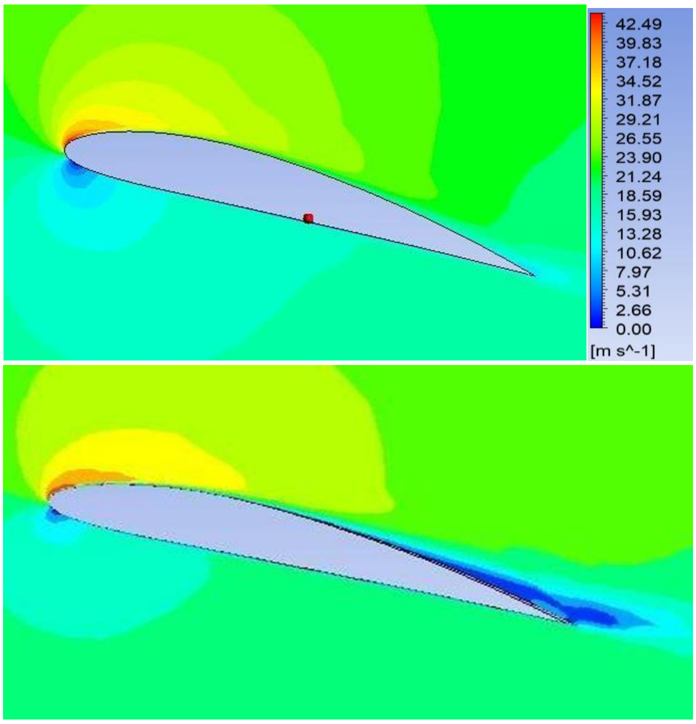


Fig 12 Velocity contour at 20° AOA with and without magnus effect mechanism

Considering the results of a selected iteration velocity contour shown in fig 12 we can observe that the magnus effect avoids the flow separation providing better aerodynamic efficiency at lower angle of attacks and comparatively higher lift value from static airfoil. The same is shown in the final data represented in terms of graphical visualization where the stall is delayed by approximately 12 degrees and maximum lift is increased by 50% positively.

Drag is 20% if the aircraft is cruising between 0-to-5-degree angle of attack with magnus mechanism. Also, in this region the aerodynamic efficiency is nearly twice considering the mean value of the region.

5. Conclusion:

After observing the analysis results, it can be concluded that:

i. The Magnus effect mechanism effectively enhances the lift coefficient, thereby preventing early flow separation.

ii. Aerodynamic efficiency of an airfoil was observed to increase by nearly twice.

iii. The stall angle of the aircraft can be significantly increased due to the Magnus effect mechanism.

iv. Also provides new capabilities to UAVs, facilitating shorter take-off and landing distances, enabling slower speeds conducive to delicate payload dropping, and enhancing surveillance capabilities with improved maneuverability.

v. Future Research Opportunities: Mechanical control surfaces may be replaced by variable-speed belts utilizing the Magnus effect and promotes the development of more streamlined and efficient aircraft designs.

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