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Software Investigation of Aerodynamic Effect of Dimples on Wing

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ABSTRACT

This research investigates the aerodynamic impact of surface dimples on aircraft wings through computational fluid dynamics (CFD) simulations. Inspired by the "golf ball theory," which demonstrates that surface indentations can delay boundary layer separation and reduce pressure drag, this study applies similar principles to aeronautical wing design. The primary objective is to enhance aerodynamic efficiency by optimizing the lift-to-drag ratio and extending the stall angle of attack. The methodology involves a comparative software analysis between a conventional smooth wing and a modified wing featuring a combination of inward and outward dimples. A NACA 6321 airfoil was selected for the base wing profile, while the dimples themselves were modeled using a symmetric NACA 0024 airfoil shape to maintain aerodynamic integrity. The investigation specifically examines the placement of inward dimples at the 0.25c and 0.75c chord positions on the lower surface, alongside outward dimples at the 0.5c chord position on the upper surface. Results from the CFD analysis indicate that these surface modifications generate localized vortices that re-energize the boundary layer, allowing the flow to remain attached to the wing surface for longer durations. This mechanism effectively narrows the low-pressure wake, thereby reducing total drag and improving lift characteristics at higher angles of attack. The findings suggest that strategically placed airfoil-shaped dimples offer a viable method for improving the maneuverability and fuel efficiency of modern aircraft.

Keywords: Aerodynamics, CFD, Boundary Layer Separation, Wing Dimples, Lift-to-Drag Ratio, NACA 6321.

1. INTRODUCTION

Aerodynamics is the core of aviation, influencing everything from subsonic to supersonic flights. Historical development of the airfoil began in the early 1800s with Sir George Cayley's discovery that curved surfaces produce more lift than flat plates. Over time, design evolved from "eyeball engineering" by pioneers like the Wright brothers to sophisticated wind tunnel research and Computational Fluid Dynamics (CFD). Today, research focuses on safety, fuel efficiency, and the optimization of aerodynamic characteristics, leading to the study of surface modifications like the "golf ball dimple theory" to control the boundary layer and delay separation. The field of aerodynamics is central to aviation, with ongoing research focused on enhancing fuel efficiency, safety, and maneuverability through the optimization of wing designs. A significant challenge in aerodynamic performance is boundary layer separation—a phenomenon where the airflow detaches from the wing surface, leading to increased pressure drag and reduced lift. The study found that airfoils with dimples experience less drag compared to plain ones. The researchers concluded that dimples create vortices that re-energize the boundary layer, delaying separation and increasing the stall angle. This is particularly useful for reducing take-off distances by achieving high lift at high angles of attack [1]. To mitigate these effects, various surface modifications such as vortex generators and riblets have been traditionally employed to delay flow separation. Inspired by the "golf ball theory," this project investigates the application of surface dimples on aircraft wings to improve aerodynamic characteristics. Much like the dimples on a golf ball transition the boundary layer from laminar to turbulent to reduce wake size, strategically placed wing dimples can re-energize the boundary layer through localized vortices. The some investigation provided a comparative study of boundary layer thickness between dimpled and smooth designs. It confirmed that golf ball-style dimples are a viable alternative for drag reduction in aeronautical applications by controlling flow separation [4].

The study tested round, square, triangular, and elliptical shapes. It concluded that placing dimples on the lower surface of the airfoil is the most effective configuration for improving aerodynamic efficiency compared to the upper surface or both sides [2]. After analyzing square, rectangular, and triangular dimples, the researchers found that **square dimples** yielded the best results for enhancing lift and decreasing drag on a NACA 2412 airfoil [5].

This study utilizes Computational Fluid Dynamics (CFD) to analyze the impact of airfoil-shaped dimples on a NACA 6321 wing profile. By comparing a conventional smooth wing with a dimpled configuration, this research explores how such modifications can effectively delay stall and optimize the lift-to-drag ratio.

1.1. The Boundary Layer Theory

When fluid flows over a solid body, a thin layer called the boundary layer forms adjacent to the surface. In this layer, velocity varies from zero at the surface to the free stream velocity, and the layer's thickness increases along the length of the object.

1.1.1. Laminar Boundary Layer Flow: This is a very smooth flow that creates less skin friction drag than turbulent flow but is generally less stable.

1.1.2. Turbulent Boundary Layer Flow: At a certain distance from the leading edge, the smooth laminar flow breaks down and transitions into a turbulent flow containing swirls and eddies. While it creates more friction, it is better at remaining attached to the surface. The research highlighted that dimples induce turbulence at lower Reynolds numbers. This provides extra momentum to the boundary layer, which creates smaller wake or swirl regions, ultimately reducing total drag and increasing lift [3].

1.2. The Boundary Layer Separation

Flow separation occurs when the boundary layer detaches from a surface into a wake, typically when the flow slows down against an adverse pressure gradient.

Consequences: In aerodynamics, separation results in reduced lift, increased pressure drag, and can cause aircraft stalling or structural buffeting.

1.2.1. Present Methods to Delay Separation: Traditional methods include vortex generators and leading-edge cuffs, which re-energize the boundary layer with localized vortices. These devices create a turbulent boundary layer that can remain attached to the wing much longer than a laminar one.

1.3. The Golf Ball Dimple Theory

This theory is based on the observation that a dimpled golf ball can travel nearly twice as far as a smooth one.

Mechanism: Dimples create a thin turbulent boundary layer that clings to the ball's surface, allowing air to follow the curvature further around the back.

Drag Reduction: By delaying separation, dimples create a narrower low-pressure wake, which significantly reduces pressure drag.

Application to Wings: This concept can be applied to aircraft wings by placing dimples at the separation point to keep the flow attached, thereby reducing drag and increasing the lift coefficient compared to a simple airfoil.

2. LITERATURE SURVEY

The literature survey within the project reviews different research and journal papers focused on the aerodynamic impact of surface modifications, specifically dimples, on wings and airfoils.

Key findings from the major sources cited include:

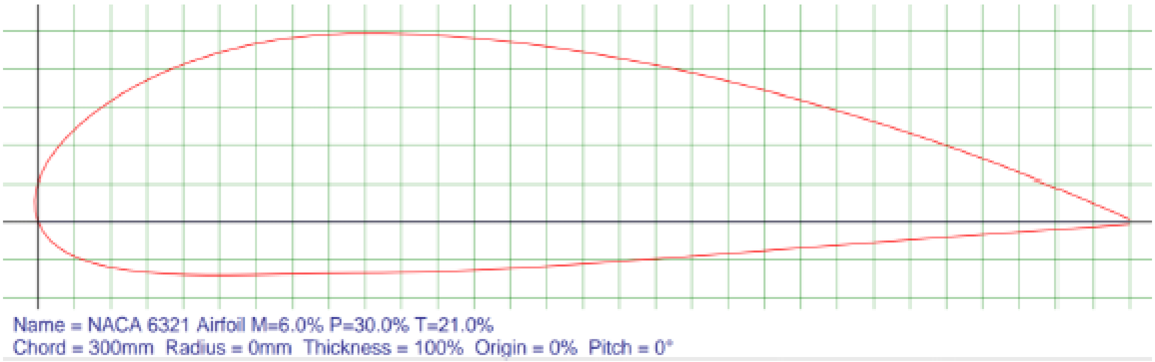
- **Numerical Investigation Over Dimpled Wings:** A study involving circle, heart, and elliptical dimples on a NACA 6321 airfoil concluded that dimpled surfaces have less drag than plain surfaces. The dimples create turbulence through vortices, which delays boundary layer separation and increases the stall angle.
- **Performance Enhancement via Corrugated Foils:** Inspired by birds and insects, researchers found that corrugations (acting like dimples) on flapping foils help in the timely growth and travel of the leading-edge vortex, improving aerodynamic performance.
- **Impact of Dimple Geometry on NACA 0012:** Research on round, square, triangular, and elliptical dimples showed that adding these shapes improves efficiency by delaying flow separation. Notably, placing dimples on the lower surface was found to be the best configuration for efficiency compared to the top surface.
- **Optimized Dimple Shapes for NACA 2412:** Previous studies analyzed by the authors demonstrated that dimples induce turbulence at lower Reynolds numbers. This provides extra energy to the boundary layer, leading to smaller wake regions and a reduction in total drag.

- **Golf Ball Theory Application:** This investigation compared the boundary layer thickness between dimpled and smooth NACA series airfoils. It predicted that using golf ball-inspired dimples is a viable alternative for drag reduction by optimizing the location and curvature of the dimples.
  The overarching theme across the surveyed literature is that dimples act as a method of passive flow control, re-energizing the boundary layer to remain attached to the wing surface for a longer duration, thereby reducing pressure drag and enhancing lift.

3. DESIGN OF WING

The wing design incorporates specialized aerodynamic surface modifications (dimples) to delay flow separation and improve performance.

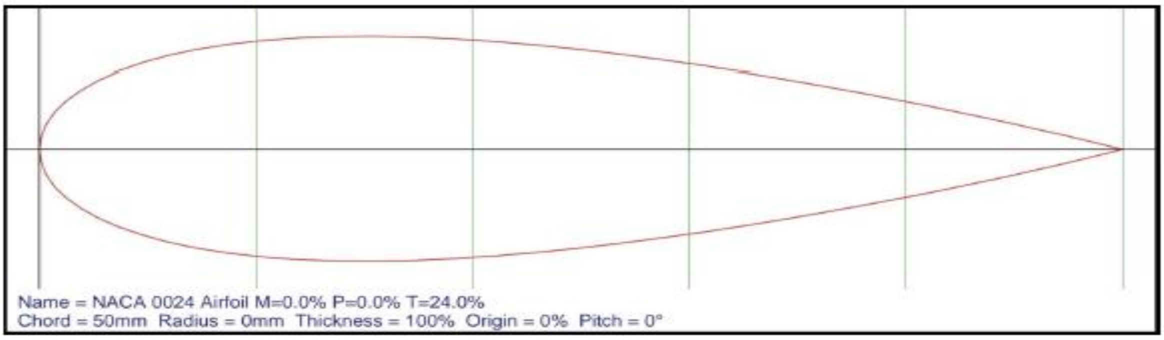
3.1. Airfoil Selection: The wing design is based on the NACA 6321 airfoil. This specific airfoil was selected because it is a flat-bottom airfoil, which is generally more efficient and provides a better lift-to-drag ratio than high-camber airfoils.



3.2. Wing Dimensions: The physical model of the wing was constructed with the following specifications:
- **Span (Length):** 450 mm.
- **Chord (Width):** 300 mm.
- **Thickness:** 100 mm.

3.3. Dimple Geometry and Design

The project utilizes a unique "aerofoil-shaped" dimple rather than standard spherical ones to ensure smoother airflow and reduce high-pressure regions at the dimple boundaries.
- Dimple Shape: The dimples are modeled after the NACA 0024 symmetric airfoil.
- Dimple Size: Each dimple has a chord length of 50 mm.
- Types of Dimples: The design uses both inward dimples (to help flow stick to the surface) and outward dimples (which act as vortex generators).



3.4. Dimple Placement: The dimples are arranged in single rows of 15 dimples each, with a 25 mm distance between the centers of pressure of adjacent dimples. They are located at specific percentages of the wing's chord length (c):

Position	Dimple Type
1/4 of chord at lower surface	Inward
1/2 of chord at upper surface	Outward
3/4 of chord at lower surface	Inward

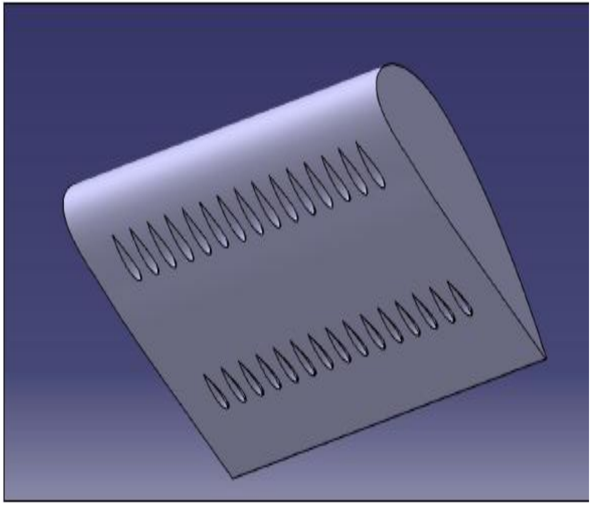


Fig. Inward dimple on wing as per decided position.

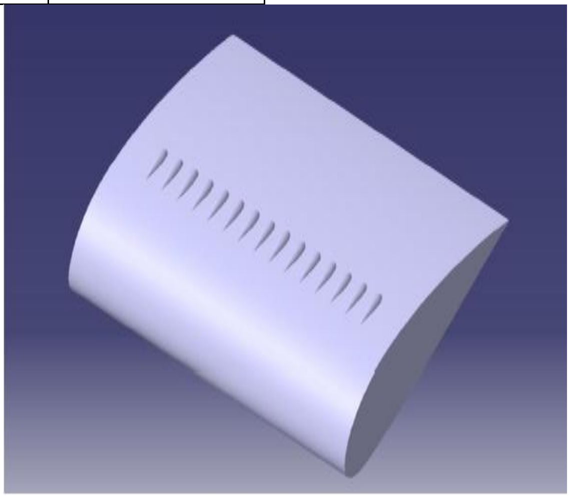


Fig. Outward dimple on wing as per decided position

4. MESHING

Meshing is a critical step in Computational Fluid Dynamics (CFD) that involves dividing a continuous physical domain into a discrete number of small sub-domains, known as elements or cells. This process allows for the numerical solution of complex fluid flow equations over and around the wing.

4.1. Mesh Generation

In this project, the geometry of the wing (based on the NACA 6321 airfoil) and its surface modifications (dimples) are discredited into a grid. The accuracy of the simulation is highly dependent on how well this mesh captures the physical properties of the wing, such as the curved surfaces and the sharp edges of the dimples.

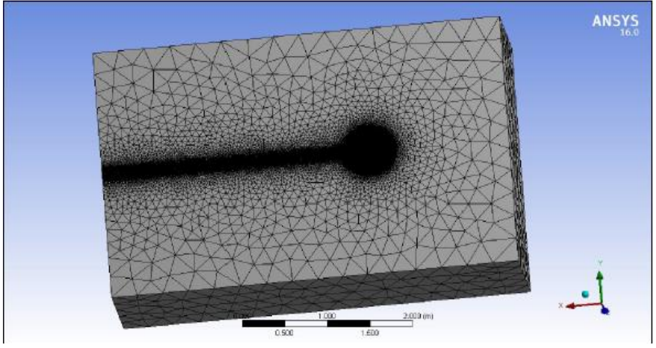


Fig. Meshing (Unstructured mesh)

4.2. Mesh Quality and Adaption

- **Mesh Quality:** The reliability of the results depends on the quality of the individual cells. Factors like cell skewness and aspect ratio are monitored to ensure the simulation converges accurately.
- **Mesh Adaption:** This technique is used to refine the mesh in specific areas where the fluid flow is complex, such as near the wing's surface (the boundary layer) or around the dimples where vortices are generated.

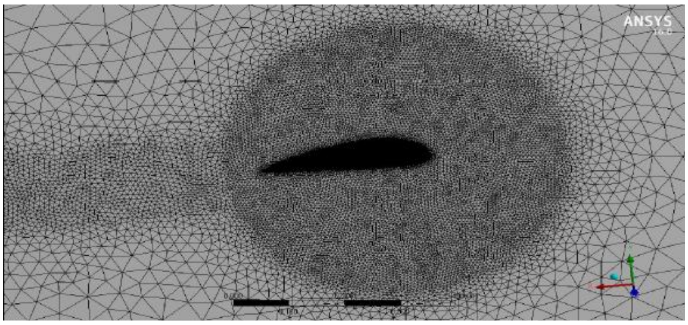


Fig. Mesh quality (fine) also shows Sphere of influence over wing

4.3. Types of Meshing Used

The report identifies two primary types of meshes used in aerodynamic analysis:

- **Structured Mesh:** These have a regular, grid-like pattern where each interior vertex has the same number of adjacent elements. They are typically more accurate for simple geometries but harder to implement for complex shapes.
- **Unstructured Mesh:** These are composed of irregular elements (like triangles or tetrahedrons) and are better suited for the complex geometries used in this project, such as the specific placement of 15 dimples in various configurations.

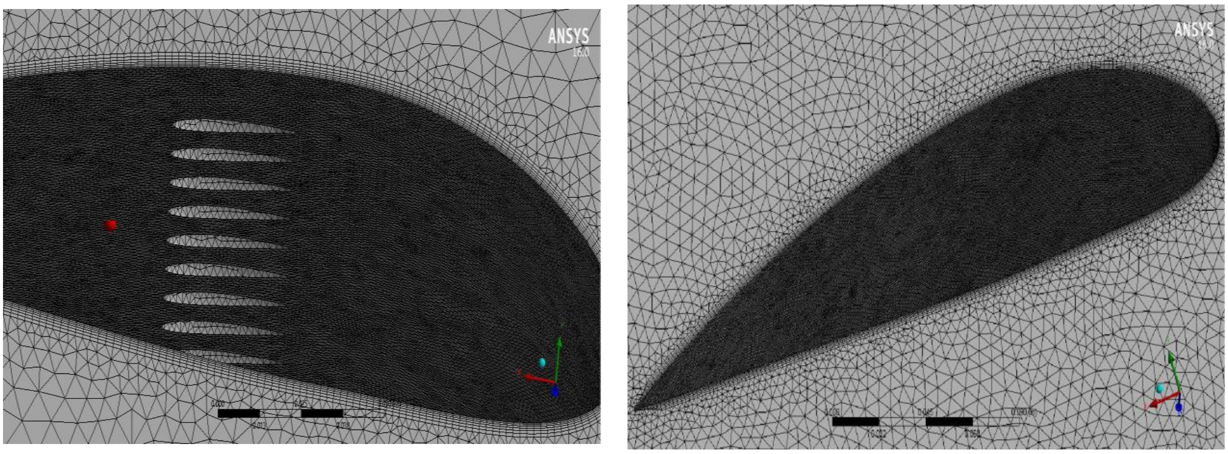


Fig. Meshing on Dimpled wing (above) and Plain wing (below)

4.4. Mesh Movement

Mesh movement is relevant for simulations where the wing might be subjected to different angles of attack (AOA) to study the variation in lift (CL) and drag (CD). This allows the same mesh structure to be utilized while changing the flow orientation.

5. RESULTS AND DISCUSSION

This section focuses on the comparative analysis between a plain NACA 6321 wing and a modified wing featuring airfoil-shaped dimples. The study used ANSYS Fluent to analyze aerodynamic performance at various angles of attack (AOA) ranging from -10° to 35° at a constant Reynolds number of 50,000.

5.1. Core Findings on Aerodynamic Performance

- **Lift Enhancement:** The dimpled wing showed a significant increase in the coefficient of lift (CL) compared to the plain wing, particularly between angles of attack of -10° to 25°.
- **Drag Reduction:** While the surface modifications introduced some insignificant drag increases at certain angles, the overall drag variation was considered negligible when compared to the substantial lift gains. For the highest angles of attack (30° and 35°), the drag on the dimpled wing was actually lower than that of the simple wing.
- **Stall Delay:** The dimples successfully acted as passive flow control devices, creating turbulence that delayed boundary layer separation and increased the stall angle.

5.2. Impact of Dimple Geometry and Placement

- **Pressure Distribution:** Introducing dimples on the upper surface reduced pressure values, while dimples on the lower surface increased pressure. This increased pressure differential resulted in better upward lift.

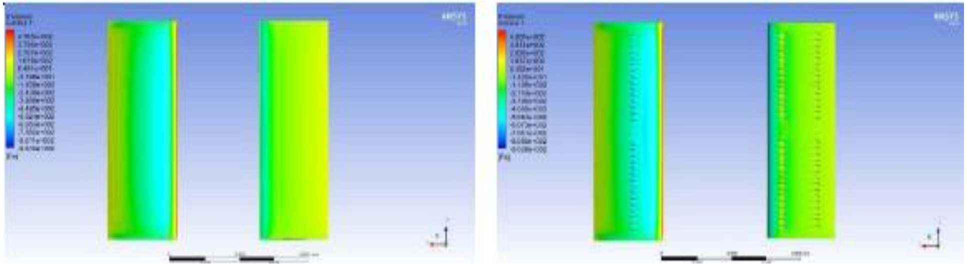


Fig. Pressure Distribution over Wing Surface

- **Effective Configuration:** The most effective setup involved placing an outward dimple at 25% of the chord on the top surface and inward dimples at 25% and 75% of the chord on the lower surface.
- **Aerofoil-Shaped Dimples:** The use of NACA 0024 symmetric airfoil-shaped dimples was found to be more efficient than standard semi-spherical dimples because they reduced high-pressure region formation at the dimple boundaries, maintaining better overall lift.

5.3. Physical Phenomena Observed

- **Coanda Effect:** The attachment of the boundary layer over the dimples is attributed to the "Coanda effect," where the dimple surface creates a suction force or low-pressure region that keeps the flow attached for a longer duration.

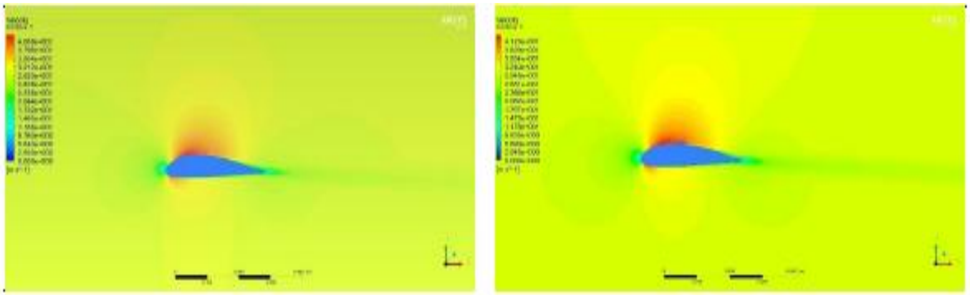


Fig. Conda Effect

- **Vortex Generation:** The outward dimples on the upper surface acted as vortex generators, re-energizing the boundary layer and ensuring that flow separation occurred further toward the trailing edge.

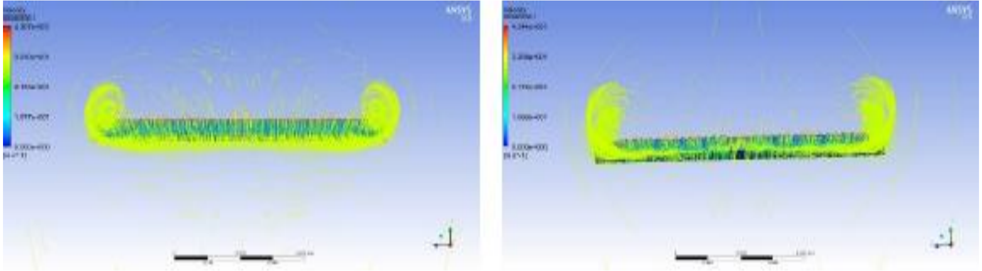


Fig. Vortex Generation

- **Pressure Gradients:** Simulation results confirmed that the upper surface experienced lower pressure (suction) while the lower surface experienced higher pressure, effectively pushing the wing upward. Most of this lift was generated at the front edge of the wing

6. CONCLUSIONS

The study concludes that incorporating airfoil-shaped dimples on a wing surface significantly enhances its aerodynamic performance by manipulating the boundary layer.

The key conclusions are:

- **Delay of Flow Separation:** The dimples act as passive flow control devices, creating turbulence that delays boundary layer separation. This delay allows the airflow to remain attached to the wing for a longer duration, reducing the low-pressure wake region.
- **Lift Enhancement:** The modified wing showed a significant increase in the coefficient of lift (C_L) compared to a plain wing, particularly at angles of attack between -10° and 25°.

- **Drag Reduction and Efficiency:** While the dimples may cause minor drag increases at certain angles, the overall drag variation is negligible when compared to the substantial lift gains. At high angles of attack (30° and 35°), the drag on the dimpled wing was actually lower than that of the plain wing.
- **Effective Configuration:** The most effective results were achieved using NACA 0024 symmetric airfoil-shaped dimples. Specifically, placing an outward dimple at 25% of the chord on the upper surface and inward dimples at 25% and 75% on the lower surface proved to be a highly satisfactory arrangement for maintaining aerodynamic efficiency.
- **Physical Phenomena:** The attachment of the boundary layer over the dimples is attributed to the "Coanda effect," where the dimple surface creates a suction force that keeps the flow attached. Additionally, outward dimples on the upper surface function as vortex generators to re-energize the boundary layer.

  In summary, the use of airfoil-shaped dimples is a viable and efficient method to improve aircraft maneuverability and potentially reduce take-off distances by increasing lift at lower velocities

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