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Aerodynamic Evaluation of a Symmetrical Airfoil Using Wind Tunnel Testing

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تقييم ديناميكي هوائي لجنيح متماثل باستخدام اختبارات نفق الرياح

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Abstract:
This research presents a detailed examination of the aerodynamic characteristics of a symmetrical airfoil through wind tunnel testing conducted at various angles of attack. The experiments carried out at the University of Hartford, were designed to evaluate how different angles of attack affect the airfoil's aerodynamic properties, with particular focus on identifying the onset of stall conditions. The results demonstrated that the airfoil experiences a stall at a critical angle of attack of 21.8 degrees, marked by a sharp decline in lift and a simultaneous increase in drag, indicating substantial changes in aerodynamic forces. Observations made before and after this critical point provide essential insights into the shift from stable to unstable aerodynamic conditions, offering valuable information for optimizing airfoil designs in real-world applications. Beyond the experimental results, the study also includes a thorough review of various airfoil profiles and wind tunnel types, providing a comprehensive context for their relevance in aerodynamic research. The discussion covers the specific applications of different airfoil shapes and the benefits and drawbacks of different wind tunnel configurations, ranging from subsonic to transonic and supersonic flow conditions. By combining empirical data with an extensive literature review, this research provides a strong foundation for understanding the key factors influencing airfoil performance. The findings highlight the importance of accurately determining critical stall angles to enhance aircraft safety and efficiency, contributing significantly to the advancement of aerodynamic studies.

Keywords: Aerodynamics, Angle of Attack, Stall Recovery, Symmetrical Airfoil, Wind Tunnel Testing.

الملخص:
يقدم هذا البحث دراسة تفصيلية للخصائص الديناميكية الهوائية لجنيح متماثل من خلال اختبارات نفق الرياح التي أجريت عند زوايا هجوم مختلفة. صُممت التجارب، التي نُفذت في جامعة هارتفورد الأمريكية، لتقييم كيفية تأثير زوايا الهجوم المختلفة على الخصائص الديناميكية الهوائية للجنيح، مع تركيز خاص على تحديد بداية حالات الانهيار . أظهرت النتائج أن الجنيح يمر بانهيار عند زاوية هجوم حرجة تبلغ 21.8 درجة، يتميز بانخفاض حاد في الرفع وزيادة متزامنة في السحب، مما يشير إلى تغييرات كبيرة في القوى الديناميكية الهوائية. توفر الملاحظات التي تم جمعها قبل هذه النقطة الحرجة وبعدها رؤى أساسية حول الانتقال من الظروف الديناميكية الهوائية المستقرة إلى غير المستقرة، مما يقدم معلومات قيمة لتحسين تصميمات الجنيحات في التطبيقات الواقعية .بالإضافة إلى النتائج التجريبية، يتضمن الدراسة مراجعة شاملة لمختلف أشكال الجنيحات وأنواع أنفاق الرياح، مما يوفر سياقًا شاملاً لأهميتها في البحث الديناميكي الهوائي. تغطي المناقشة التطبيقات المحددة لأشكال الجنيحات المختلفة وفوائد ومساوئ تكوينات أنفاق الرياح المختلفة، بدءًا من ظروف التدفق تحت الصوتي إلى الانتقالي وفوق الصوتي. من خلال الجمع بين البيانات التجريبية ومراجعة أدبية موسعة،

يقدم هذا البحث أساسًا قويًا لفهم العوامل الرئيسية التي تؤثر على أداء الجنيحات. تبرز النتائج أهمية تحديد زوايا الانهيار الحرجة بدقة لتعزيز سلامة وكفاءة الطائرات، مما يساهم بشكل كبير في تقدم الدراسات الديناميكية الهوائية.

الكلمات المفتاحية: ديناميكا هوائية، زاوية الهجوم، استعادة الانهيار، جنيح متماثل، اختبارات نفق الرياح.

1. Introduction

Aerodynamics involves examining how air moves and interacts with solid objects, such as the wings of an aircraft, vehicle bodies, and other structures. The way air flows around these objects is essential to their design and functionality, especially in aviation, where aerodynamics significantly affects lift, drag, and the overall stability of an aircraft. A thorough understanding of airfoil aerodynamics is vital for creating safer and more efficient aircraft. This study offers valuable experimental insights into the performance of a symmetrical airfoil, emphasizing the critical angle of attack at which a stall occurs. By investigating the lift and drag forces at different angles of attack, this research enhances the knowledge needed to optimize airfoil designs for various flight conditions. These findings enable engineers to design aircraft that reduce the risk of stalling, enhance fuel efficiency, and maintain stable flight dynamics. Additionally, the results support pilot training programs by improving understanding of stall behavior and recovery methods, contributing to greater aviation safety[1-6].

A. Lift and drag forces:

Lift and drag are the two primary aerodynamic forces that affect an aircraft in flight. Lift is the force that acts perpendicular to the direction of airflow, enabling the aircraft to rise and remain airborne. It is generated by the pressure difference between the upper and lower surfaces of the airfoil, primarily shaped by the curvature (camber) of the wing and the angle of attack. The angle of attack is the angle between the chord line of the airfoil and the oncoming airflow. As the angle of attack increases, the lift initially increases due to a greater pressure differential across the airfoil surfaces. Drag, on the other hand, is the resistance force that acts parallel and opposite to the direction of the airflow. It is composed of two main components: freeloading drag (due to the shape and surface of the aircraft) and induced drag (a consequence of lift). Engineers aim to minimize drag while maximizing lift to improve fuel efficiency, reduce wear and tear, and enhance the overall performance of the aircraft [5-8].

B. Stall and recovery from stall:

As the angle of attack increases, there is a point where the smooth airflow over the airfoil begins to separate from the surface, creating turbulent wake regions. This phenomenon is known as stall. Stall occurs when the lift generated by the airfoil rapidly decreases, and drag sharply increases, causing a sudden loss of altitude and control. The critical angle at which a stall occurs varies with airfoil design, airspeed, and flight conditions but typically ranges between 15 and 20 degrees for most conventional airfoils.

Recovering from a stall involves reducing the angle of attack to allow the airflow to reattach to the airfoil surface, thereby restoring lift. Pilots achieve this by lowering the aircraft's nose, increasing airspeed, and adjusting the control surfaces. Effective stall recovery is critical for maintaining flight safety and preventing accidents [3,7, 8].

C. Thrust and weight:

Thrust and weight are two additional forces that play a vital role in an aircraft's flight dynamics. Thrust is the forward force produced by the aircraft's engines, propelling it through the air. It counteracts drag and allows the aircraft to accelerate. Weight, due to gravity, acts downward and opposes lift. For steady-level flight, the thrust must equal drag, and the lift must equal weight. Maintaining this balance is essential for controlled and sustained flight [9-11].

D. Relevance of wind tunnel testing:

Wind tunnels are critical tools in aerodynamic research, allowing engineers to simulate and analyze airflow over various shapes and structures in a controlled environment. By testing different airfoils at various angles of attack in wind tunnels, researchers can study the aerodynamic forces, optimize designs, and predict real-world performance [12].

This study focuses on wind tunnel testing of a symmetrical airfoil to analyze its aerodynamic characteristics, particularly lift, drag, and stall behavior at different angles of attack. Understanding these characteristics is crucial for designing safe and efficient aircraft.

E. Types of airfoils

Airfoils are structures specifically designed to generate lift as air flows over them, with different shapes optimized for distinct performance needs. Symmetrical airfoils, with identical upper and lower surfaces, produce no lift at a zero angle of attack and are favored in situations like aerobatic flight or helicopter rotors where inverted flight or minimal pitching moment is needed. Cambered airfoils, featuring a curved upper surface and flatter lower surface, generate lift even at zero angle of attack and are commonly used in commercial aircraft for their high lift coefficients, improving fuel efficiency and reducing takeoff and landing distances. Supercritical airfoils, ideal for high-speed flight near or beyond the speed of sound, feature a flattened upper surface and a highly cambered aft section to reduce drag from shock waves, making them suitable for modern jets. Laminar flow airfoils are designed to maintain smooth airflow over a large portion of the wing to reduce drag, often used in sailplanes and light aircraft. The selection of an airfoil type depends on the specific aerodynamic performance and operational requirements [9-15].

F. Types of wind tunnels:

Wind tunnels are crucial instruments in aerodynamic research, enabling the simulation and analysis of airflow over various objects. Different types of wind tunnels are designed for specific testing conditions. Low-speed wind tunnels, operating below 100 m/s (about 225 mph), are used for subsonic testing, making them suitable for automotive and low-speed aircraft applications; they can be either open-circuit or closed-circuit to recirculate air and reduce power use. High-speed wind tunnels, functioning at speeds from Mach 0.3 to 0.8 or beyond, are essential for examining transonic and supersonic conditions, playing a key role in designing jet aircraft, rockets, and other high-speed vehicles. Hypersonic wind tunnels, which operate at speeds exceeding Mach 5, allow for the study of conditions faced by re-entry vehicles, missiles, and future spaceplanes, often using high-pressure air sources and specialized nozzles. Variable density wind tunnels adjust air density by altering pressure, facilitating precise simulations of different altitudes and atmospheric conditions. While not technically wind tunnels, water tunnels are also used to visualize fluid flow around objects at lower Reynolds numbers, aiding in qualitative studies of flow patterns, separation, and turbulence. The choice of wind tunnel type depends on the specific research goals, including speed range, model scale, and the need for pressure or density variation[16,17].

G. Problem statement:

The performance of an airfoil, particularly under different angles of attack, is fundamental to the design and operation of any aircraft. However, the critical angle at which a symmetrical airfoil stalls and the associated changes in aerodynamic forces are not always well-documented, especially for different flight speeds and conditions. Numerous studies [18-28] have employed both Computational Fluid Dynamics (CFD) and experimental techniques, such as wind tunnel testing, to evaluate aerodynamic characteristics under various conditions.

This study addresses the lack of experimental data on symmetrical airfoils by conducting wind tunnel tests to determine the angle of attack at which stall occurs and to observe the corresponding changes in lift and drag forces. The objective is to identify the aerodynamic characteristics that influence stall behavior and to provide experimental data that can be used to refine aircraft design and safety techniques.

2. Material and methods

The wind tunnel at the University of Hartford is made up of several essential components that work together to facilitate aerodynamic testing. The test section is where models or objects are placed to analyze airflow and collect data. The air intake and contraction cone accelerate incoming air to ensure a uniform flow into the test section. The fan and drive system, powered by an electric motor, generates the required wind speeds, while the diffuser, positioned downstream, slows the airflow to reduce turbulence and allow efficient exhaust. Measurement instruments, such as pressure sensors, force balances, and flow visualization tools, capture data on lift, drag, pressure, and flow patterns. The data acquisition system processes and displays this information in real time, while the control room contains the computer systems that manage airflow, fan speed, and other conditions. Finally, a support structure provides stability and integrity to the entire tunnel assembly, see Figure 1, and Figure 2.

A. Experimental setup and procedure:

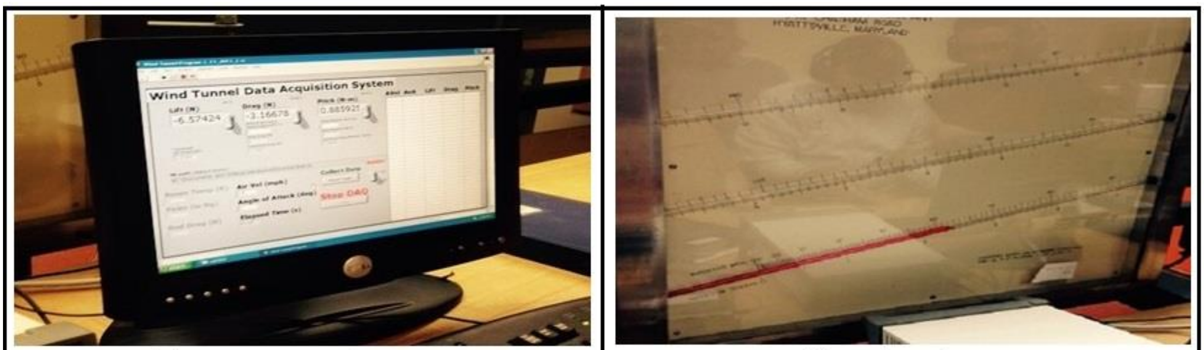
The experiment was carried out in a low-speed wind tunnel at the University of Hartford, specifically designed for subsonic aerodynamic testing (Figure 1). The test utilized a symmetrical airfoil (Figure 2c), which was securely mounted in the wind tunnel, and airflow speed was maintained at a constant 62 mph. The data collection process involved the following detailed steps:

- The airfoil was carefully mounted in the test section of the wind tunnel to ensure accurate positioning and secure attachment.
- The wind tunnel was warmed up to stabilize the internal environment, ensuring consistent airflow conditions throughout the experiment.
- The computer control system was activated, and the test program was initialized to monitor and adjust test parameters (Figure 2a).
- The airflow speed was precisely set to 62 mph, as confirmed by the tunnel's control interface and sensors (Figure 2b).
- The airfoil was initially aligned at a zero-degree angle of attack, establishing a baseline for data collection (Figure 2c).
- Initial aerodynamic data, including lift, drag, and pressure distribution, were collected using the wind tunnel’s data acquisition system, which recorded real-time measurements from various sensors (Figure 2d).
- The angle of attack gradually increased in increments of 2 to 5 degrees, systematically monitoring the airflow characteristics until the stall condition was detected at 21.8 degrees.

- After reaching the stall angle, the angle of attack was reduced in 2-degree intervals, with data recorded at each decrement until the airfoil returned to the original zero-degree angle, ensuring comprehensive data across the full range of angles tested.

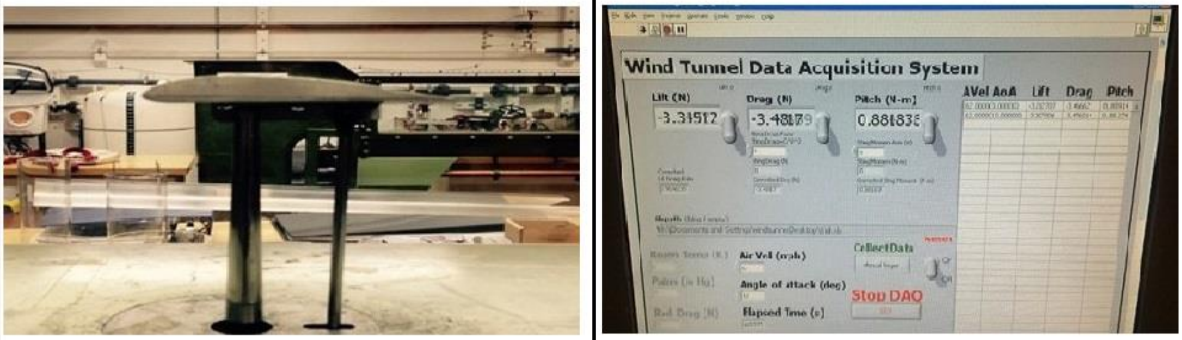
This systematic approach allowed for precise measurement and analysis of the aerodynamic properties of the airfoil under varying conditions.

Figure 1 : A low-speed wind tunnel at the University of Hartford.



(a) Computer control system.

(b) Speed panel



(c)Airfoil at Zero angle of attack

(d) Data acquisition system

Figure 2 : Key components of the wind tunnel at the University of Hartford, illustrating the integrated systems used for aerodynamic testing and data collection.

3. Results and discussion

The wind tunnel experiments conducted at a fixed airflow speed of 62 mph provide a comprehensive overview of the aerodynamic performance of a symmetrical airfoil, with the results summarized in Table and detailed analyses shown in Figure 3, and Figure 4. The main aim of this study was to understand how varying the angle of attack influences lift and drag forces on the airfoil.

Table 1: Summary of the experimental results.

Air velocity(mph)	Angle of attack (degree)	Lift (N)	Drag (N)
62	0	-3.282707	-3.466621
62	5.7	-3.307906	-3.476014
62	10.2	0.106328	-3.932229
62	18.8	1.884599	-4.611370
62	21.8	1.085231	-5.618896
62	24.7	-3.596168	-8.206762
62	19.8	-1.818189	-6.750622
62	18.8	0.722488	-5.901043
62	16.7	1.454290	-5.162361
62	11.3	0.159626	-4.160619
62	0	-7.038299	-3.458480

Figure 3 illustrates how lift varies with changes in the angle of attack. The lift force increases as the angle of attack rises, reaching a maximum value of 1.88 N at 18.8 degrees, and continues to increase until the airfoil stalls at 21.8 degrees, achieving a peak lift of 1.09 N. This pattern aligns with aerodynamic principles, which predict an increase in lift up to a critical point where stall occurs due to airflow separation. The stall was observed at 21.8 degrees, consistent with typical behavior for symmetrical airfoils. After reaching the stall angle, the lift decreases significantly, as depicted in Table and Figure 3. Beyond this critical angle, further increases in the angle of attack result in a substantial drop in lift due to the onset of turbulence and flow separation around the airfoil. Reducing the angle of attack post-stall shows a minor recovery in lift, suggesting partial reattachment of airflow, but the lift does not return to its pre-stall values. The lift approaches zero as the angle of attack is decreased back to zero degrees, indicating the airfoil's performance limitations and confirming its symmetrical characteristics.

fixed airflow speed of 62 mph, the angle of attack was gradually increased to measure the resulting aerodynamic forces. As shown in Figure 3, lift increased with the angle of attack until it peaked at 21.8 degrees, where stall occurred. This behavior aligns with theoretical expectations, where stall typically occurs at angles greater than 15 degrees. After stall, reducing the angle of attack resulted in a slight lift recovery before approaching zero as the angle returned to zero degrees. Figure 4 demonstrates that drag decreased initially with increasing angle of attack, but sharply increased after reaching the stall point. Understanding these aerodynamic behaviors is crucial in aircraft design to ensure safety and optimize performance. Knowing the critical stall angle for different airfoils helps engineers design safer aircraft by preventing unintended stalls during flight.

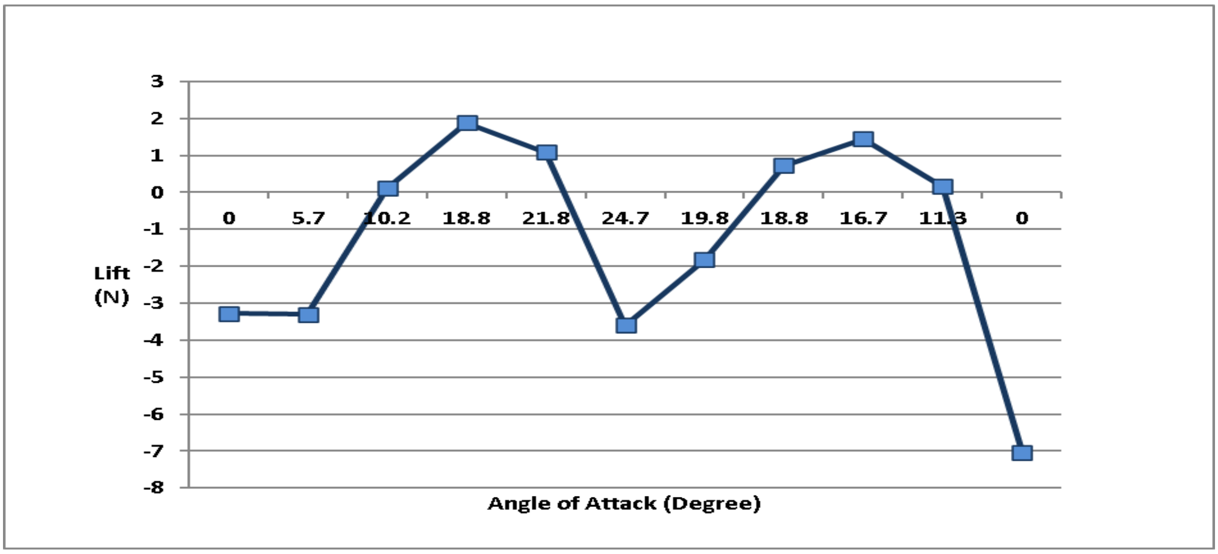


Figure 3 Relationship between lift and angle of attack.

Figure 4 shows the variation in drag with respect to the angle of attack. At first, drag decreases slightly as the angle of attack increases, but this trend reverses sharply after the stall point is reached. The data reveals that drag peaks at -5.62 N at the stall angle of 21.8 degrees, and increases dramatically afterward, reaching a maximum of -8.21 N at 24.7 degrees. This substantial rise in drag after the stall is typical of aerodynamic flow separation, where turbulent wakes form behind the airfoil, increasing resistance. As the angle of attack is gradually reduced following the stall, the drag begins to decrease, reflecting a partial recovery of laminar flow around the airfoil, although not to the original levels due to persistent turbulence and flow disturbances.

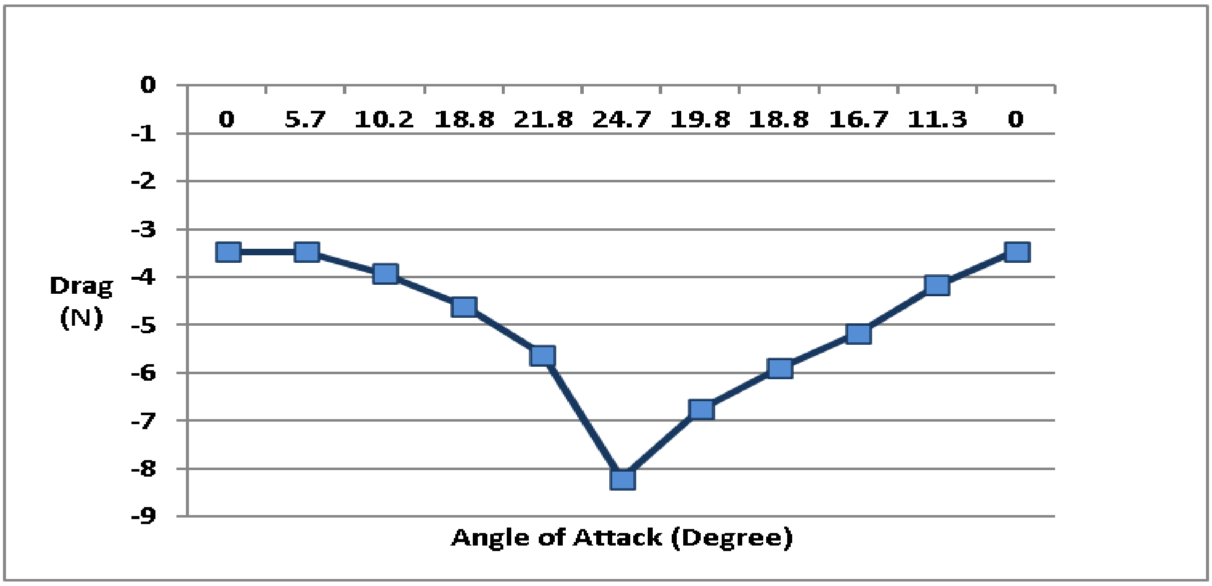


Figure 4 Relationship between drag and angle of attack.

The insights gained from understanding the relationship between lift, drag, and the angle of attack are critical for enhancing the safety and performance of aircraft. Identifying the critical stall angle at 21.8 degrees is particularly valuable for airfoil design, as it allows engineers to define safe operating limits and prevent unintended stalls during flight. This understanding is crucial in developing airfoils that ensure both safety and efficiency. Moreover, the marked increase in drag beyond the stall angle highlights the importance of maintaining an angle of attack below the critical threshold to maximize aerodynamic efficiency and minimize fuel consumption. The findings from this experiment are essential for refining the design of various aircraft, from general aviation to high-performance models, to ensure optimal performance within aerodynamic constraints.

4. Conclusion

The wind tunnel experiments provided a systematic understanding of the aerodynamic behaviors of a symmetrical airfoil across various angles of attack at a constant speed, with results aligning closely with theoretical expectations. Key findings included the identification of the critical stall angle at around 22 degrees, which is vital for understanding and optimizing airfoil performance under different flight conditions. While the experiment was successful in capturing the relationships between lift, drag, and angle of attack, minor errors occurred due to manual adjustments, highlighting areas for improvement in measurement precision. These findings contribute valuable data for the design and optimization of safer, more efficient aircraft. The observed aerodynamic characteristics, particularly the stall behavior and drag trends, are crucial for enhancing aircraft safety and performance by establishing clear operational limits.

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