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Investigating the Influence of Maximum Camber, Amplitude and Frequency of Oscillation on the Hysteresis Characteristics of an Oscillating Airfoil

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Abstract

In this study, the hysteresis characteristics of an oscillating airfoil are investigated (around a.c.) to showcase the influence of geometrical and cyclic parameters (i.e., the maximum camber, amplitude, and frequency of oscillation). Hence, NACA0012, 1412, 2412, 3412, and 4412 airfoils were analyzed for an oscillation amplitude of 10° and a frequency of 2.5 Hz. Assuming an amplitude of 10° for NACA4412, this is repeated to evaluate the effect of the oscillation amplitude, and for frequencies of 1, 2.5, and 4 Hz to study the effect of oscillation frequency. In addition to the characteristics related to the overall shape of the graphs (depicting lift, drag, and pitching moment coefficients vs. angular velocity and angle of attack), such as the direction of rotation, twist, and deformity, the area enclosed in the hysteresis loops matters, which allows analysis of the transmitted power or wasted energy. While the deformity is generally caused by the flow separation on the upper surface of the airfoil, the twist of the loops can be caused by the out-of-phase movement of the airfoil regarding the flow. It can be observed that the more the airfoil is cambered, the better the lift coefficient, while strongly changing the drag and pitching moment coefficients.

Keywords: Oscillating Airfoil, Flow Separation, Hysteresis, Aerodynamic Coefficients.

1. Introduction

The aerodynamics of airfoils are often simpler and less costly to study than complex three-dimensional flow over wings. This is considered one of the first steps in the fluid dynamics analysis of flying objects. Although the flow regimes over 3D wings and airfoils differ, the aerodynamic properties of wings directly depend on the airfoil used [1]. Airfoils at low Reynolds numbers (below 500,000) exhibit unique behaviors, such as the transition from laminar to turbulent flow, flow separation, and stall [2]. These behaviors enhance the aerodynamic performance, especially at high angles of attack.

Exploring the aerodynamic properties of airfoils at low Reynolds numbers is crucial, because stall is one of the most limiting factors for airfoil performance [3]. While stationary airfoils are highly sensitive to flow separation and stall at low Reynolds numbers, their behavior changes significantly when oscillating [4]. For instance, unlike static conditions, flow separation bubbles on oscillating airfoils are constrained, and turbulent flow prevails, delaying stall and causing hysteresis [5, 6].

Hysteresis, a characteristic observed in dynamic systems, leads to different aerodynamic behaviors during upward and downward movements [9]. This phenomenon results from the phase difference between the airfoil motion and flow field [10]. Researchers have studied hysteresis by examining the closed-loop patterns in aerodynamic coefficient graphs, which provide insights into the flow behavior and separation events [11, 12].

Other factors, such as the oscillation frequency and geometry, also influence the flow dynamics. Studies have shown that increasing the oscillation frequency can reduce the hysteresis loop area and delay flow separation [3]. Airfoil geometry, particularly camber, significantly affects flow, but its systematic exploration in oscillating airfoils remains limited [13, 16].

This study focuses on examining the effects of airfoil camber, oscillation amplitude, and frequency to achieve optimal performance by analyzing the hysteresis loop quality, area, and extremum points. [5, 7, 8].

2. Methodology

This study focuses on the flapping motion of an airfoil in a two-dimensional flow, primarily by analyzing its oscillation around a fixed axis in a steady free stream. The governing equations describe the airfoil's angular velocity as a function of time, and the aerodynamic forces, lift, drag, and moment are presented through dimensionless coefficients. The boundary layer effects are analyzed using hysteresis loops, whose shapes and enclosed areas reflect the impact of these effects. The area under these loops was numerically calculated and interpreted as the specific power transferred to the flow during one oscillation cycle.

2-1. Geometrical Conditions

The simulations were conducted for five NACA four-digit airfoils, each with a thickness of 12% and chord length of 300 mm. The geometric specifications and analysis conditions are presented in Table 1, and the computational domain is illustrated in Fig. 1. The analysis was performed using both steady and transient methods: steady-state analysis with variable angles of attack for comparison with numerical wind tunnel results and transient analysis using a fixed time step and a constant angular velocity for dynamic simulations.

All simulations were performed under standard sea level conditions, resulting in an air density of 1.225 kg/m³ and a dynamic viscosity of 1.7894×10^{-5} kg/m·s.

Table 1. Geometrical Specifications of Models and Analysis Conditions

AIRFOIL	FLOW VELOCITY (M/S)	REYNOLDS NUMBER	SOLUTION METHOD
NACA0012	10	167,000	Transient
NACA0012	20	335,000	Steady
NACA2412	10	167,000	Transient
NACA4412	10	167,000	Transient
NACA4412	10	167,000	Steady

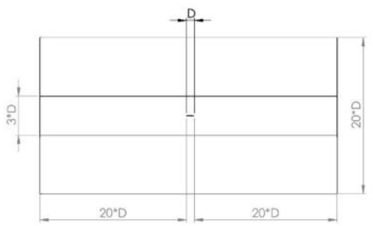
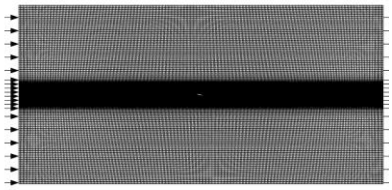


Figure 1. Computational Domain Geometry

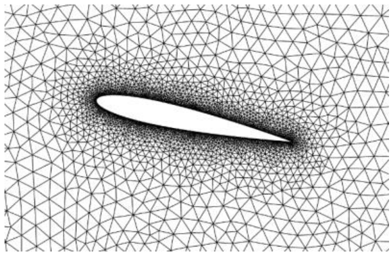
2-2. Meshing

The mesh consisted of 65,000 elements, combining triangular elements near the dynamic domain and structured meshing around the airfoil (Figure 2), with a y+ value ranging from approximately 6 to 250 around the airfoil. The simulation time varied based on the frequency, and four full oscillation cycles were simulated with a time step of 0.0005 s. Owing to the excessive skewness of the mesh elements caused by the airfoil movement within the domain, remeshing is required, which is only feasible for triangular or hexagonal meshes in ANSYS Fluent.

To ensure mesh independence, simulations were conducted with mesh densities of 100,000, 65,000, and 30,000 elements, respectively. It was observed that, for a mesh with 65,000 elements, the error rate was approximately 0.05%, ensuring stable results across different mesh densities. Thus, a mesh with 65,000 elements was selected for analysis.



A View of the Mesh Generated in the Analysis Domain



B View of the Mesh Generated with Triangular Elements Near the Airfoil

Figure 2. Views of the Mesh Generated Around the Airfoil

Given the lack of reliable experimental data for most of the airfoils studied in this research, validation of the results was performed using experimental data from the OA309 airfoil in a flow with a Reynolds number of 9×10^5 and a frequency of 2 Hz [15]. comparison between the experimental data and numerical validation results, demonstrating a good agreement between the two. A closer examination reveals some discrepancies at higher angles of attack, which are common in similar studies [20, 21]. Li et al. explored the effect of numerical methods and turbulence models on these differences in their research [19].

2-3 Solution Method

The solver used in this study was Fluent from the ANSYS software, configured with a pressure-based approach (M<0.3). The turbulence model employed is the K–ε realizable enhanced wall treatment, which utilizes the URANS equations to analyze the viscous properties of the flow. The Realizable model uses modified values from the standard method and performs better in the curved boundary layers. An Enhanced wall treatment is more suitable for engineering applications [17].

In simulations, the y+ value must be set within the appropriate range for the turbulence model. For example, the y+ values for the K–ε model using standard wall functions should be between 30 and 300 to ensure that the first cell lies within the logarithmic layer [18]. The Enhanced Wall Treatment models the flow behavior near the wall, justifying the use of y+ ≈ 6-250 in this study (with some points between 6 and 30).

In addition, the URANS equations have a relatively low computational load. The solution time using RANS models is up to 50 times faster than that of solving the full Navier-Stokes equations [21]. In this study, both steady simulations (with varying angles of attack for comparison with wind tunnel results) and transient simulations (with a fixed time step and angular velocity at a constant frequency) were used for the dynamic analysis.

2-4. Analysis Patterns

The analysis patterns were designed to examine the effects of the three variables on the dynamic behavior of the oscillating airfoil.

1. Airfoil curvature,
2. Oscillation amplitude,
3. Oscillation frequency.

2-4-1. Curvature of the Airfoil:

The influence of airfoil curvature was explored using NACA0012, NACA2412, and NACA4412 airfoils, all of which were subjected to a frequency of 2.5 Hz and an oscillation amplitude of 10 °. Each simulation included four complete cycles, with a time step of 0.0005 s.

2-4-2. Oscillation Amplitude:

The impact of the oscillation amplitude was analyzed by maintaining a constant mean angle and varying the amplitude from low to near-stall angles. Three oscillation amplitudes (±5°, ±10°, and ±15°) are tested on the NACA4412 airfoil at a frequency of 2.5 Hz over 4 complete cycles.

2-4-3. Oscillation Frequency:

The effect of frequency on aerodynamic behavior was studied by testing frequencies of 1, 2.5, and 4 Hz on the NACA4412 airfoil with a 10-degree oscillation amplitude. The simulations included a time step of 0.0005 s and spanned four complete cycles.

3. Discussion and Results

The analysis results include the effects of airfoil curvature (NACA0012, NACA1412, NACA2412, NACA3412, and NACA4412), the effect of oscillation amplitude (5, 10, and 15 degrees for the NACA4412 airfoil), and finally, the effect of oscillation frequency (frequencies of 1, 2.5, and 4 Hz for the NACA4412 airfoil) under a free-stream flow with a velocity of 10 meters per second.

3-1. Effect of the Airfoil Camber

The analysis highlights how the airfoil curvature, oscillation amplitude, and frequency affect aerodynamic performance. An increased curvature increases the lift coefficient (Cl) and drag coefficient (Cd), with the drag increasing significantly during upward motion and remaining low during downward motion. The rotational moment coefficient (Cm) also increases with the curvature owing to the greater pressure differences on the airfoil surfaces. This "induced curvature" effect mimics a higher curvature during upward motion. The oscillation amplitude and frequency further influence the lift, drag, and moment loops, with larger amplitudes and higher frequencies intensifying hysteresis effects. The curvature typically reduces the hysteresis loop size, indicating lower energy dissipation for more curved airfoils.

3-2. Results of Oscillation Amplitude Variation

The analysis covers the lift coefficient versus the angle of attack and drag, lift, and moment coefficients versus angular velocity for three amplitudes—5°, 10°, and 15 °—at 2.5 Hz using the NACA 4412 airfoil. The key factor is the oscillation amplitude, which affects the size and area of the hysteresis loop. Larger amplitudes generally lead to larger loop areas; doubling the amplitude can increase the loop area up to four times. Using the intensity as a comparison parameter, the results show a higher hysteresis intensity with increased amplitude. At 15 °, stall signs and irregularities appear during the downstroke, causing greater energy dissipation. Drag curves reveal flow separation and significant warping at 15 °, indicating a dynamic stall delay that occurs at 10 °, which is higher than the static stall angle.

3-3. Frequency Variation results

The analysis involves plots of the lift coefficient (Cl) versus the angle of attack and the coefficients of lift, drag, and moment versus angular velocity for a 10-degree amplitude at different frequencies using the NACA 4412 airfoil. At 1 Hz, the lift coefficient plot showed considerable warping and a reduced loop area. At 2.5 Hz, the warping diminishes, and at 4 Hz, the loop is fully opened. This trend indicates a transition from a negative to a positive enclosed area, reflecting the positive work performed by the lift. Similar behavior was observed in the moment coefficient plots. For the drag coefficient, higher frequencies lead to lower maximum and minimum values owing to the reduced flow adhesion. The enclosed area in each loop, representing the work per cycle, increases with frequency, with data for 1, 2.5, and 4 Hz compiled, including curve slopes and areas.

4. Conclusions

In this study, the oscillation of airfoils in a free stream was analyzed, focusing on the flapping motion at the quarter-chord point. This study aimed to explore variations in the drag, lift, moment coefficients with respect to the camber, oscillation amplitude, and frequency.

Airfoils from the NACA four-digit series (NACA 0012, 1412, 2412, 3412, and 4412) were used, with a maximum thickness of 12% at a 40% chord length. The NACA 4412 airfoil was tested at frequencies of 2.5 Hz with amplitudes of 5°, 10°, and 15 °, and simulations were conducted at frequencies of 1, 2.5, and 4 Hz with a 10-degree amplitude.

Increasing the camber from zero to 4% chord increases the drag coefficient with respect to the angle of attack without causing a stall. While the work done per cycle for drag remained constant, the enclosed area of the hysteresis loop increased. The enclosed area for the moment coefficient loops initially decreased and then showed a minimal change.

Increasing the oscillation amplitude with a constant frequency shows significant effects on flow separation at higher angles of attack. The hysteresis intensity parameter was used to quantify these effects, revealing an increased intensity at higher amplitudes.

Increasing the oscillation frequency affects the maximum drag coefficient. While drag is higher during the upstroke owing to better flow adhesion, higher frequencies lead to a flow lag and a reduced maximum drag coefficient. At 4 Hz, more net work was performed, corresponding to the hysteresis loop opening in the moment coefficient plot.

This study aims to provide a conceptual framework for understanding how changes in geometric and cyclic parameters affect the dynamic performance of oscillating airfoils, focusing on hysteresis and loop shape. While numerical analysis offers preliminary estimates, experimental validation and detailed simulations are essential for an accurate performance assessment and understanding.

Future work should refine the interpretation of the enclosed areas in hysteresis loops and investigate separation bubbles and streamlines for deeper insights. Experimental validation is crucial for verifying the numerical results, and defining appropriate performance metrics is essential for evaluating simulation conditions.

5. References

[1] Zhu C, Qiu Y, Wang T (2021) Dynamic Stall of the Wind Turbine Airfoil and Blade Undergoing Pitch Oscillations: A Comparative Study. *Energy* 222:1200-04

[2] Carmichael B, NASA (1982) Low Reynolds Number Airfoil Survey.

[3] Phan M, Shin J (2016) Numerical Investigation of Aerodynamic Flow Actuation Produced by Surface Plasma Actuator on 2D Oscillating Airfoil. *Chinese J Aeronaut* 29:882–892

[4] Aiken E, Ormiston R, Young L (2000) Future Directions in Rotorcraft Technology at Ames Research Center. NASA Moffett Field CA Aimes Research Center.

[5] Lee T, Gerontakos P (2004) Investigation of Flow over an Oscillating Airfoil. *J Fluid Mech* 512:313–341

[6] Corke T, Thomas F (2015) Dynamic Stall in Pitching Airfoils: Aerodynamic Damping and Compressibility Effects. *Annu Rev Fluid Mech* 47:479–505

[7] Zou S, Gao A, Shi Y, Wu J (2017) Causal Mechanism Behind the Stall Delay by Airfoil's Pitching-up Motion. *Theor Appl Mech Lett* 7:311–315

[8] Mayer YD, Zang B, Azarpeyvand M (2020) Aeroacoustic Investigation of an Oscillating Airfoil in the Pre- and Post-Stall Regime. *Aerosp Sci Technol* 103:105880

[9] Morris KA (2011) What is hysteresis? *Appl Mech Rev* 64:161-73

[10] Eslami Haghighat Z (2022) Experimental Investigation of Suddenly Stop of Supercritical Airfoil SC-0410 between Pitching Motion In Persian, *J Aeronaut Eng.* 3 (2) :29-42

[11] Soltani MR, Rasi Marzabadi F (2010) Experimental Investigation of Transition on a Plunging Airfoil. *Sci Iran* 17 (6): 468-489

[12] Yang Z, Haan F, Hu H, Ma H (2007) An Experimental Investigation on the Flow Separation on a Low-Reynolds-Number Airfoil. In: 45th AIAA aerospace sciences meeting and exhibit. p 275

[13] Mueller T (1985) The Influence of Laminar Separation and Transition on Low Reynolds Number Airfoil Hysteresis. *J Aircr* 22:763–770

[14] Heydari A, Pasandideh Fard M, Malek Jafarian M (2012) Investigation of Unsteady Parameters Effects on Aerodynamic Coefficients of Pitching Airfoil Using Coarse Grid CFD, In Persian, *J Aeronaut Eng.* 14 (2) :49-66

[15] Martinat G, Braza M, Hoarau Y, et al (2008) Turbulence Modelling of the Flow Past a Pitching NACA0012 Airfoil at 10^5 and 10^6 Reynolds Numbers. *J Fluids Struct*, 1294:303–24

[16] Zhiping L, Zhang P, Tianyu P, et al (2020) Study on Effects of Thickness on Airfoil-Atall at Low Reynolds Numbers by Cusp-Catastrophic Model Based on GA (W)-1 airfoil. *Chinese J Aeronaut* 33:1444–1453

[17] Guo B, Liu P, Qu Q, Cui YL (2012) Turbulence Models Performance Assessment for Pressure Prediction During Cylinder Water Entry. *Appl Mech Mater* 224:225–229

[18] Shokrgozar Abbasi A, Yazdani S (2021) A Numerical Investigation of Synthetic Jet Effect on Dynamic Stall Control of Oscillating Airfoil. *Sci Iran* 28:343–354.

[19] Li Z, Zhang P, Pan T, et al (2018) Catastrophe-Theory-Based Modeling of Airfoil-Stall Boundary at Low Reynolds Numbers. *AIAA J* 56:36–45

[20] Masdari M, Jahanmiri M, Soltani M et al (2016) Experimental Investigation of Boundary Layer on an Oscillating Supercritical Airfoil, Sharif Mech J, 8: 41-52

[21] Medina A, Alves D, de Paula Sales T, et al (2014) Study of Flow over and Oscillating NACA0012 Airfoil. In: 8th Ntl. Cong. of Mech. Eng.