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Comparison of the Aerodynamic Characteristics between NACA0012 and NACA4412 Helicopter Rotor Airfoils under Severe Convective Conditions

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Abstract. Severe convective weather often accompanies with the high turbulence intensity and the vertical gust interference, which can strongly affect helicopter rotors during low-altitude flight and can easily cause dynamic stall, and threaten flight safety. This paper investigates two airfoils with the same geometric thickness: the symmetric airfoil (which is NACA0012) and the cambered airfoil (which is NACA4412). This paper compares them using published wind-tunnel experimental data and published CFD studies. The lift force, drag force, pitching moment, and flow-separation characteristics of the two airfoils under the severe convective disturbances are compared to see how geometric parameters can influence the disturbance resistance of rotor airfoils. The results show that NACA4412 airfoil has better static lift performance and it is able to generate greater lift at lower speeds, whereas the symmetric NACA0012 airfoil has smaller load fluctuations under the gust disturbances, better stall resistance, and better operating stability under adverse severe-convective conditions.

Keywords: Helicopter rotor, NACA airfoil, severe convective weather, camber, aerodynamic characteristics

1. Introduction

When a helicopter flies at low altitude in severe convective environments with strong turbulence and disturbed airflow, the incoming flow contains strong short-term disturbances [1]. The angle of attack of the rotor blades can change quickly, so dynamic stall is more likely. The dynamic-stall process involves unsteady vortices and complex aerodynamic interference, and can lead to unsteady aerodynamic problems such as a sudden drop in rotor thrust and sharp increases in reaction torque and blade vibration, which limits helicopter flight speed and maneuverability [2]. As a basic part of a rotor blade, the airfoil responds directly to camber under severe convective disturbances.

NACA0012 is a classic symmetric airfoil widely used in helicopter rotors. NACA4412 has a maximum camber of 4%, located at 40% of the chord, and can generate greater lift under static conditions. Because the two airfoils have the same thickness and mainly differ in camber, they are useful for comparing how camber affects aerodynamic characteristics under severe convective conditions. This study compares the lift, drag, pitching moment, flow separation, and dynamic-stall

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behavior of the two airfoils under steady inflow and severe-convective gust disturbances, to provide a reference for rotor-airfoil selection in adverse weather conditions [2].

2. Numerical method

2.1. Airfoil geometric characteristics

As show in Figure 1, NACA0012 is a symmetric airfoil. It produces zero lift at a zero angle of attack, its aerodynamic behavior is similar at positive and negative angles of attack, and its pitching-moment level is low.

NACA4412 is a positively cambered airfoil. It generates lift even at a zero angle of attack and has a higher static lift coefficient, but its stall angle of attack is smaller and its pitching moment is larger [3, 4].

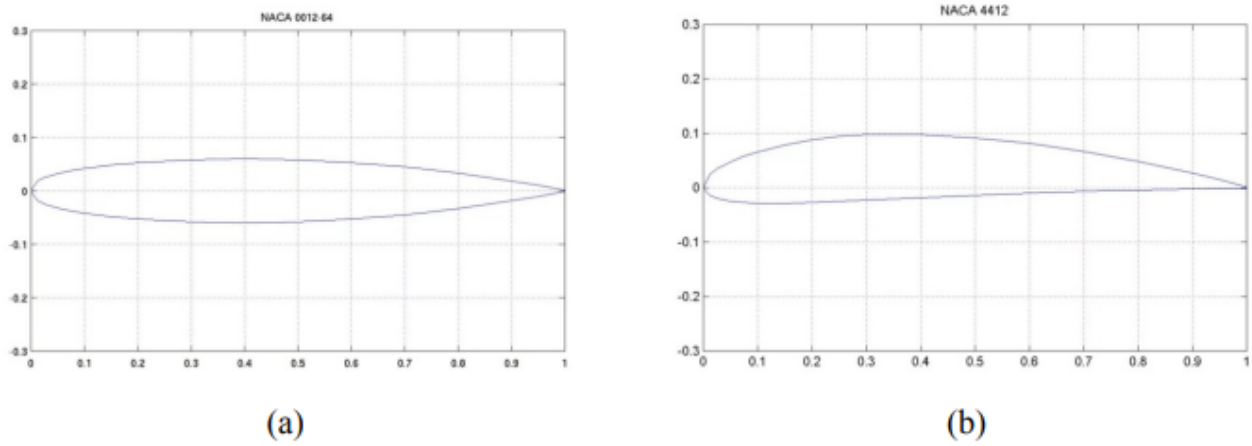

Figure 1. NACA0012(a) and NACA4412(b)with the same chord length

$$C_L = \frac{L}{0.5\rho V^2 S} \tag{1}$$

$$C_D = \frac{D}{0.5\rho V^2 S} \tag{2}$$

$$C_M = \frac{M}{0.5\rho V^2 S c} \tag{3}$$

Where L is lift; D is drag; M is pitching moment; ρ is air density; V is free stream velocity; S is reference area; and c is the airfoil chord length.

2.2. Severe convective conditions and dynamic stall

As show in Figure 2, during helicopter forward flight, the retreating blade operates at a high angle of attack and may also enter a reverse-flow region, so dynamic stall is more likely. When external gust

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disturbances are added, load fluctuations become stronger; so the airfoil's response to gusts needs to be studied [5].

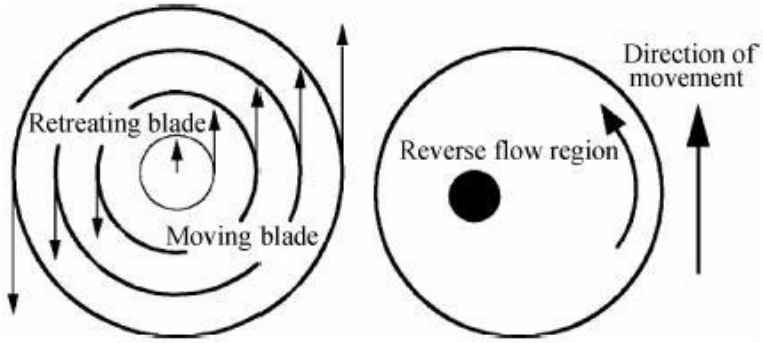

Figure 2. Helicopter rotor velocity distribution and flow-field characteristics

Low-altitude severe convective environments have high turbulence intensity together with periodic vertical gusts, causing the actual blade angle of attack to rise and fall quickly. When the instantaneous effective angle of attack exceeds the static stall angle, dynamic stall occurs. Large-scale flow separation occurs over the upper surface, lift drops sharply, drag rises rapidly, and a clear hysteresis loop appears. These effects cause large alternating loads that can damage the rotor structure [6].

2.3. Turbulence model

As show in Figure 3, the k-ω SST turbulence model gives good computational accuracy both outside the boundary layer and in the near-wall region, and works well for simulating dynamic airfoil separation and dynamic stall under gust disturbances. It is therefore widely used in related research. Gusts are time-varying unsteady disturbances, and steady calculations cannot fully capture dynamic stall or oscillating alternating loads; these effects need to be studied using unsteady RANS methods. This paper does not carry out a separate numerical simulation, but uses the flow mechanisms associated with this model for qualitative analysis [7].

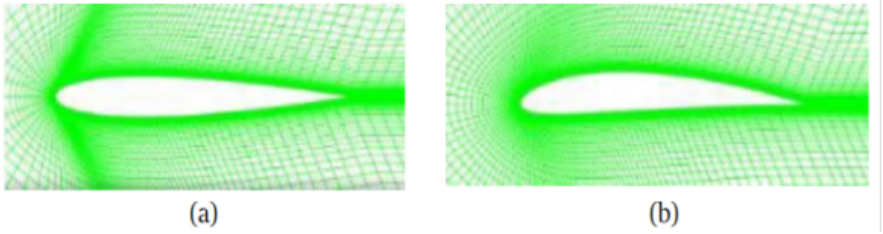

Figure 3. Mesh generating for NACA0012(a) and NACA4412(b)

3. Results and discussion

3.1. Steady inflow conditions

Shown in Figure 4, Under steady-flow conditions, NACA4412 has a higher lift coefficient and a better lift-to-drag ratio than NACA0012, but it stalls earlier, with a static stall angle of approximately 14-15°. NACA0012 has a lower maximum lift, a symmetric response to positive and

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negative angles of attack, a more gradual stall, and a smaller pitching-moment coefficient than NACA4412 [3, 4].

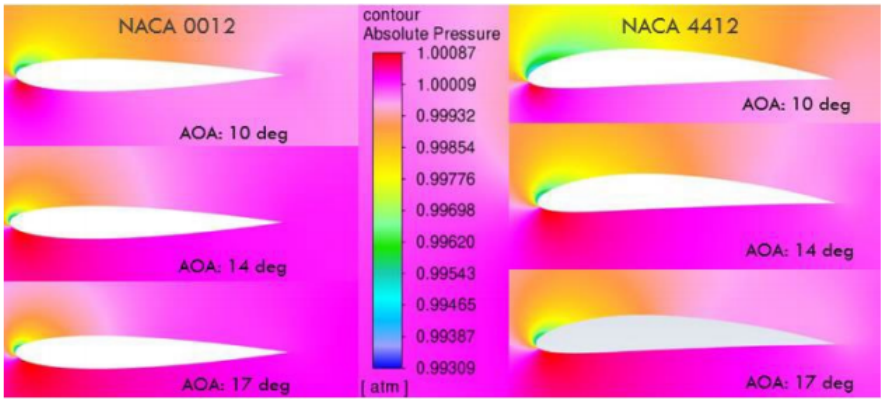

Figure 4. Pressure distribution around NACA0012 and NACA4412 at various angles of attack

3.2. Severe-onvective gust conditions

3.2.1. Lift and load fluctuations

NACA4412 produces more lift under static conditions. However, under vertical-gust disturbances, its effective angle of attack changes quickly and its lift shows large oscillations over time. Gusts can cause the blade to stall prematurely and cause dynamic stall; after the gust becomes weaker, the flow reattaches slowly and the hysteresis effect is strong. Although the maximum instantaneous lift of NACA0012 is lower than that of NACA4412, its lift fluctuations are smaller. It responds more steadily to upward and downward gust disturbances, is less likely to enter deep dynamic stall, and so its loads are more stable shown in Figure 5 [4, 7].

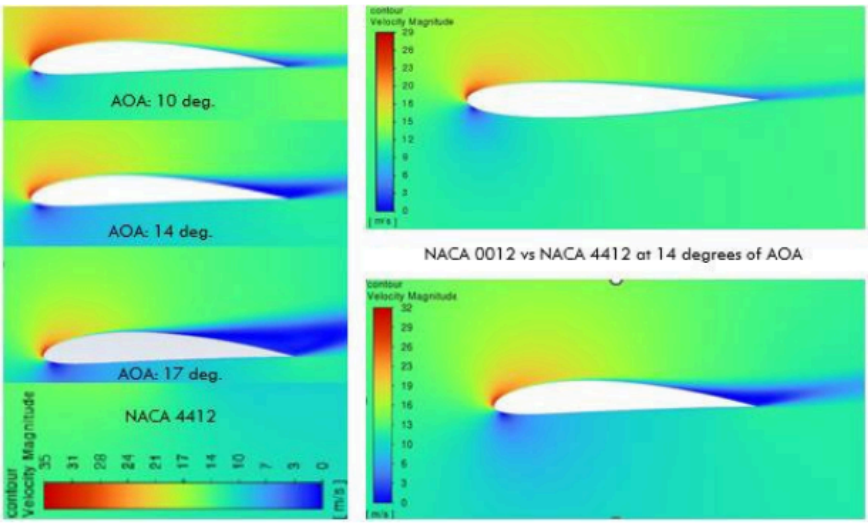

Figure 5. Velocity distributions around NACA4412 at various angles of attack and comparison between NACA0012 and NACA4412 at 14degreees

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3.2.2. Flow separation

Flow separation occurs when airflow moving along the upper surface of an airfoil can no longer stay attached to the surface, separates from it, and forms recirculating vortices. (As shown in Figure 6, the airflow gradually separates from the airfoil surface as the angle of attack increases.) Once flow separation occurs, lift decreases greatly while drag increases, and finally causes stall.

Severe convective disturbances continuously change the angle of attack. The boundary layer over the upper surface of NACA4412 separates more easily, and the separated region expands rapidly. Flow separation on NACA0012 occurs later, and its flow field recovers faster after the disturbance weakens shown in Figure 6 [8, 9].

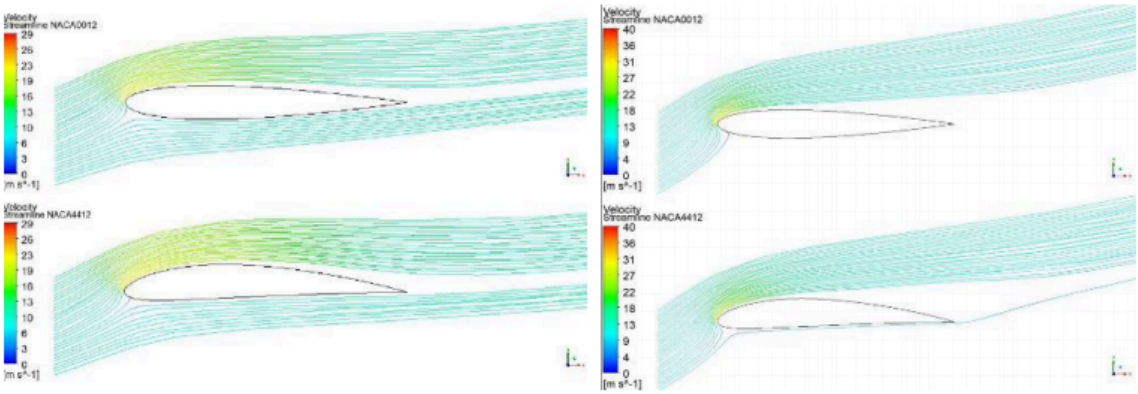

Figure 6. NACA0012 10 degrees of angle attack(a) and NACA4412 17degrees of the angle attack(b)

3.2.3. Pitching moment

NACA4412 has a large baseline pitching moment. Under gust disturbances, the moment changes strongly, causing alternating torsional loads on the blade and increasing structural vibration. NACA0012 has a lower overall pitching-moment level and smaller disturbance-induced moment fluctuations, which is better for the rotor structure [5].

3.3. Overall performance discussion

As show in Figure 7 and Figure 8, In a static environment, the cambered NACA4412 provides high lift and is suitable for designs that need high lift. However, in severe convective and turbulent environments, its lift advantage due to camber can be reduced by larger disturbance-induced load fluctuations. Cambered airfoils are very sensitive to changes in angle of attack, and vertical gusts can easily cause dynamic stall. The resulting alternating lift and pitching moment can increase rotor fatigue [10].

The symmetric NACA0012 has lower lift but handles disturbances better. It has smaller load fluctuations and weaker hysteresis, so it is more suitable for rotor components operating in regions where severe convection is frequent, and it is commonly used near the rotor root.

This paper only uses published two-dimensional sectional experimental data and flow mechanisms reported in the literature. Real helicopter rotors also need to consider three-dimensional rotation, tip vortices, and blade elastic deformation. Future studies can use three-dimensional simulations to further test these conclusions [2].

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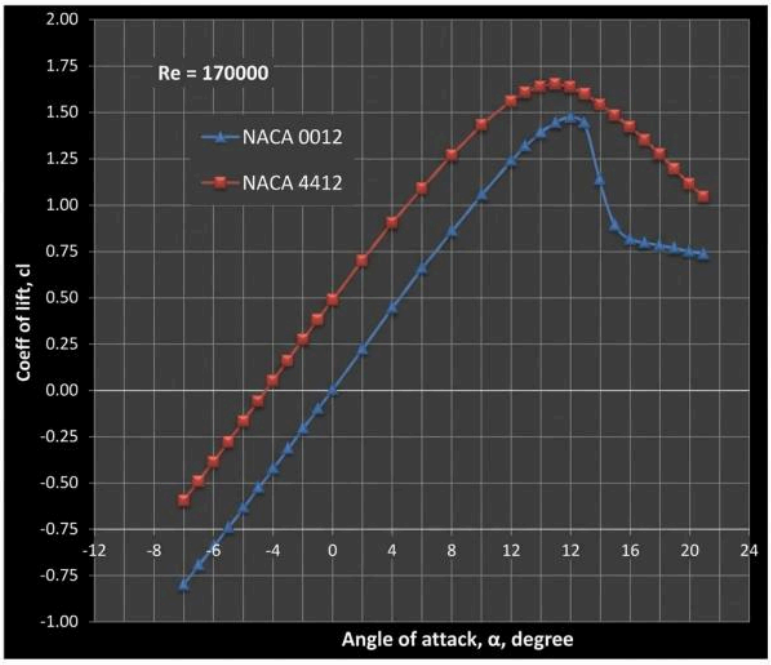

Figure 7. Comparison of lift coefficient versus angle of attack for NACA0012 and NACA4412

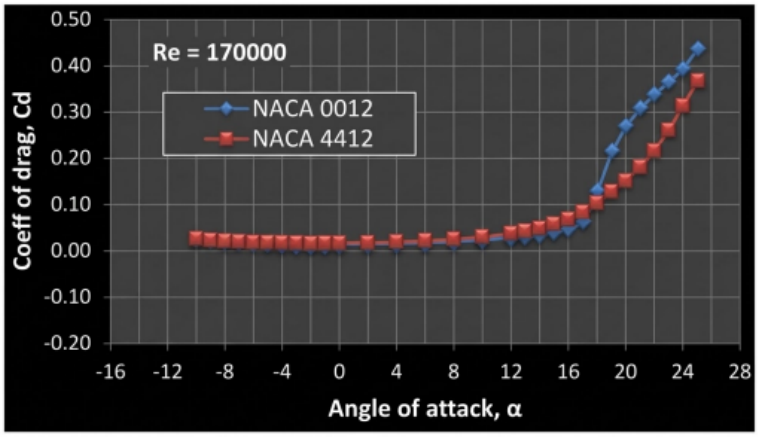

Figure 8. Comparison of drag coefficient versus angle of attack for NACA0012 and NACA4412

4. Conclusions

1. Under steady inflow conditions, NACA4412 provides higher lift and a better lift-to-drag ratio than NACA0012, but has a smaller static stall angle of attack.

2. Under vertical-gust conditions associated with severe convection, NACA4412 is more likely to enter dynamic stall, with strong aerodynamic-load oscillations and a relatively large alternating pitching-moment amplitude.

3. Although NACA0012 has a lower maximum lift, its loads remain more stable under severe convective disturbances, with weaker hysteresis and better stall resistance, so it is better suited to helicopter rotor applications under adverse weather conditions.

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