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The Current Progress of Studies on How Camber Variation Affects the Aerodynamic Performance of NACA Airfoils

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Abstract. Camber is an important factor affecting the aerodynamic performance of NACA airfoils. This paper reviews previous studies on the effects of camber variations on lift, drag, lift-to-drag ratio, pitching moment, and stall characteristics. Using the thin airfoil theory, the basic relationship between camber parameters and aerodynamic performance is introduced. Based on experimental and numerical studies, the effects of different camber magnitudes, camber positions, and camber distributions on the aerodynamic characteristics of NACA airfoils are explored. Some studies indicate that increasing positive camber at the same angle of attack can increase lift and shift the zero-lift angle of attack to negative values. However, greater camber does not always result in better aerodynamic performance. Under the certain conditions, it may also increase adverse pressure gradients, drag, pitching moment, and the risk of flow separation. The paper also discusses the prospects of variable camber airfoils for adapting aerodynamic performance to different flight conditions.

Keywords: NACA airfoil, camber variation, aerodynamic performance, lift-to-drag ratio, variable camber airfoil

1. Introduction

Geometry of an airfoil is one of the main parameters that define the lift and drag properties such as the maximum camber (m), camber position (p) and thickness (t) which are the fundamental descriptors of NACA four-digit airfoils. Altering the camber of an airfoil can make a great difference in the manner in which lift is created and hence impact on the endurance as well as the fuel efficiency of the aircraft. Over the past few years, there has been a breakthrough in technologies like smart materials and shape memory alloys, which allows making dynamic adjustments of camber in-flight, and this has received much attention in the design of fixed-wing unmanned aerial vehicles (UAVs) and energy efficient airplanes. As per the available research, it has been proven that the optimization of the airfoil camber at various stages of flight may result in fuel economy or lift-to-drag ratio improvement by several percentage points.

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2. Theoretical foundation of NACA airfoil camber parameters and aerodynamic performance

The NACA airfoils are an entire category of conventional airfoils that have been extensively used, and the geometry of these airfoils depends on both the mean camber line and the thickness distribution. In the case of four-digit airfoils, maximum camber, maximum camber position, and maximum thickness are the three main parameters that define their basic geometric features. Camber mainly changes the pressure distribution and lift bias of the airfoil, but thickness has a strong effect on the leading-edge shape, pressure recovery, and boundary layer growth. Hence, the best way to study the effects of camber variation on aerodynamic performance would be to ensure that the thickness distribution and other boundary conditions remain the same as far as possible so that the importance of the camber parameter itself can be emphasized.

2.1. Geometric definition of NACA four-digit airfoils

The NACA four-digit airfoils are usually represented by four digits to denote their fundamental geometric properties. The initial digit denotes the percentage of the ratio between maximum camber and chord length, the second digit denotes the tenths of the ratio between maximum camber position and chord length, and the final two digits denote the percentage of the ratio between maximum thickness and chord length. As an illustration, the NACA 2412 implies that the maximum camber is 2 percent of the chord length (first digit), the maximum camber is 40 percent of the chord length measured away from the leading edge (second digit), and the maximum thickness is 12 percent of the chord length (last two digits). NACA 0012 has a maximum camber of 0, hence its mean camber line is identical to the chord line and therefore it is a symmetric airfoil. With c being the airfoil chord length and x being the chordwise coordinate, the maximum camber can be written as:

$$m = \frac{y_{c,max}}{c} \tag{1}$$

The maximum camber position is expressed as:

$$p = \frac{x_{c,max}}{c} \tag{2}$$

The maximum thickness ratio is expressed as:

$$t = \frac{t_{max}}{c} \tag{3}$$

The mean camber line of NACA four-digit airfoils is made up of a forward and an aft parabolic segment, and its dimensionless form can be written as:

$$\frac{y_c}{c} = \begin{cases} \frac{m}{p^2}\left[2p\left(\frac{x}{c}\right) - \left(\frac{x}{c}\right)^2\right], & 0 \le \frac{x}{c} \le p \\ \frac{m}{(1-p)^2}\left[(1-2p) + 2p\left(\frac{x}{c}\right) - \left(\frac{x}{c}\right)^2\right], & p \le \frac{x}{c} \le 1 \end{cases} \tag{4}$$

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On this basis, the airfoil thickness distribution can be written as:

$$\frac{y_t}{c} = 5t[0.2969\sqrt{\frac{x}{c}} - 0.1260\frac{x}{c} - 0.3516(\frac{x}{c})^2 + 0.2843(\frac{x}{c})^3 - 0.1015(\frac{x}{c})^4] \quad (5)$$

The real coordinates of the upper and lower surfaces of the airfoil are also available by considering the mean camber line and thickness distribution. Hence, it is clear that NACA four-digit airfoils offer a way to represent camber and thickness in a relatively independent manner, which makes it easy to perform aerodynamic analysis of airfoils and comparative studies of airfoils with various cambers. It should be noted that the maximum camber (m) does not define the camber shape of the airfoil. Suppose there are two airfoils with the same maximum camber; in that case, various maximum camber positions (p) will cause significant changes in the shapes of the mean camber lines, surface pressure distributions, and pitching moments. The discussion of the so-called "camber effect" should then distinguish between the value of maximum camber and the positional distribution of camber in the chord direction.

When taking into account the combined impact of varying camber on lift, drag, lift-to-drag ratio, pitching moment, and stall behavior, the major aerodynamic effects are given in Table 1.

Table 1. Basic geometric characterization parameters of NACA four-digit airfoils

Parameter	Symbol	Definition	Example: NACA 2412
Maximum camber	m	Maximum camber / chord	2%
Maximum camber position	p	Position of maximum camber / chord	40%
Maximum thickness	t	Maximum thickness / chord	12%

2.2. Camber parameters and characterization methods

The term camber is generally applied to the amount of deviation of the mean camber line of the airfoil as compared to the chord line. The most commonly used geometric characterization parameters of NACA four-digit airfoils are the maximum camber ratio (m) and the maximum camber position (p). Of them, m is primarily a measure of the total camber change whereas p defines the point at which maximum camber takes place and hence both together define the general configuration of the mean camber line.

In the case of constant thickness ratio (t) and maximum camber location (p), the increase in m is typically associated with a greater positive camber of the airfoil. It is expressed directly aerodynamically as changing the pressure difference between the top surface and bottom surface of the airfoil so that the airfoil has non-zero lift at near zero angle of attack. Positive-camber airfoils typically have positive lift at zero angle of attack, and to bring lift to zero, a particular negative angle of attack must be used. Hence, a rise in camber tends to move the zero-lift angle of attack towards the negative side.

To explain the variation of camber in a more systematic way, camber parameters can be divided into three groups. The first group is maximum camber magnitude, generally represented as a percentage; the second group is maximum camber position, represented as a; the third group is the whole camber line distribution, i.e. the description of how camber changes at the chord by or its inclination. For airfoils with varying camber, the magnitude of camber deflection may also be further specified, e.g.:

DOI: 10.54254/2755-2721/2026.38259

$$\triangle m = m_{deflected} - m_{baseline} \tag{6}$$

The rate of change of camber can be given in the normalized form per unit chord length. To fully characterize the aerodynamic condition of continuous variable-camber structures, it is not enough to use only the value of the maximum camber deflection, and it is necessary to take into account the deformable region initial position, camber distribution shapes, and variations of local curvature. Hence, in the case of comparing various research findings, it might be inadequate to compare only the value of the maximum camber percentage. The same maximum camber placed at distinct chordwise positions may have significantly different pressure distributions and aerodynamic responses. The results of existing studies, whose basis is the NACA four-digit series, demonstrate that both maximum camber and its chordwise location are factors influencing lift-to-drag ratio, endurance performance, and stall behavior; hence, camber optimization is an intrinsically multi-parameter geometric optimization problem [1].

2.3. Main aerodynamic performance indicators of airfoils

The influence of camber changes on the airfoil aerodynamic behavior is commonly investigated by means of lift, drag, lift-to-drag ratio, pitching moment and stall characteristics. Dynamic pressure in two dimensional airfoil analysis is defined as:

$$q_\infty = \frac{1}{2}\rho V_\infty^2 \tag{7}$$

Where ρ is freestream density and V_∞ is freestream velocity.
The lift coefficient is defined as:

$$C_L = \frac{L}{q_\infty c} = \frac{L}{\frac{1}{2}\rho V_\infty^2 c} \tag{8}$$

The drag coefficient is defined as:

$$C_D = \frac{D}{q_\infty c} = \frac{D}{\frac{1}{2}\rho V_\infty^2 c} \tag{9}$$

Where L and D are lift and drag per unit span respectively. The lift-to-drag ratio is given by:

$$\frac{L}{D} = \frac{C_L}{C_D} \tag{10}$$

One of them is the most basic parameter that defines the lift capability of an airfoil and its relationship to the angle of attack (α) is normally depicted by a lift curve. At low angle of attack and under attached flow, the lift coefficient has an almost linear behavior as a function of angle of attack,

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slope ($\frac{dC_L}{d\alpha}$) may also be applied to measure the lift response ability of an airfoil to angle-of-attack variations.

In addition to lift and drag, the pitching moment coefficient can be used as an effective indicator of airfoil performance. Most aeronautical airfoils use the quarter chord length as the moment reference point, which defines. Variation in camber changes the pressure distribution on the forward and aft surfaces of the airfoil, which in turn changes the point of application of the aerodynamic force and the pitching moment. Hence, measurement of camber optimization effects through (C_L) and (C_D) alone might not be enough to represent its full aerodynamic effect.

However, the maximum lift coefficient and the stall angle of attack are some of the most critical indicators that can be used in assessing the performance of airfoils at high angle of attack. Once the angle of attack keeps increasing to a point where there is large-scale flow separation, no longer increases in a linear manner but eventually achieves a peak and stalls. Camber variation may improve the lift capability in the specified range of angles of attack, as well as change the process of pressure recovery and where it separates, and therefore its effect on and stall angle of attack is not monotonic.

Engineering applications of aerodynamic optimization also do not have the same objective in various flight missions. To illustrate, at cruise efficiency, is generally more significant, and at maximum lift capacity, is more emphasized; in aircraft that need to fly at high altitudes, an overall assessment of lift, drag, and power requirements is also required. The so-called optimal camber is then not a single parameter independent of operating conditions, but it should be computed simultaneously with the design angle of attack, Reynolds number, flight speed, and mission goals.

2.4. Fundamental theory of camber effects on aerodynamic performance

Thin airfoil theory is a first way of explaining the effects of camber on aerodynamic performance. Assuming that the flow is two-dimensional, incompressible, inviscid, attached to the surface with small angles of attack, thin airfoil theory provides the classical lift relationship:

$$C_L = 2\pi(\alpha - \alpha_{L=0}) \tag{11}$$

Where the angle of attack (α) is measured in radians, and ($\alpha_{L=0}$) is the zero-lift angle of attack. In the case of symmetric airfoils, the mean camber line should be on the chord line, theoretically resulting in.

$$\alpha_{L=0} \approx 0 \tag{12}$$

When the airfoil has positive camber, the mean camber line is displaced compared to the chord line, which changes the distribution of the circulation over the upper and lower surfaces, producing positive lift at null angle of attack and moving the zero-lift angle of attack to a negative value. Thus, in the region of attached flow, it can be said that the primary effect of the increase of positive camber is the upward displacement of the whole curve and not the significant alteration of the theoretical lift curve slope.

Further considering the mean camber line ($y_{c(x)}$) and adopting the variable transformation:

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$$\frac{x}{c} = \frac{1-\cos\theta}{2} \tag{13}$$

The thin airfoil theory may be used to characterize the angle of attack at which there is no lift by using the slope of the mean camber line. The general form of its equation can be expressed as:

$$\alpha_{L=0} = \frac{1}{\pi}\int_0^{\pi} \frac{dy_c}{dx}(1-\cos\theta)d\theta \tag{14}$$

As can be inferred through this, the zero-lift angle of attack is associated with not just the maximum camber magnitude, but also the camber distribution on the chord. It also suggests that maximum camber (m) and maximum camber position (p) are linked to each other: varying p modifies the spatial variation of the mean camber line slope; regardless of whether m is constant or not, the final pressure distribution, lift, and pitching moment may change significantly. Nonetheless, thin airfoil theory is based upon ideal flow hypothesis and cannot explain the real world effects of viscosity, transition, flow separation, and stall. When the camber increases in actual flow, the velocity and pressure distributions on the airfoil surface are changed, which causes redistribution of the suction peak, pressure recovery process, and adverse pressure gradients. On the one hand, proper camber could enhance the pressure difference at the target angles of attack and thus, increase lift; on the other hand, excessive local curvature and pressure recovery might increase the adverse pressure gradients and make the boundary layer more prone to separation, increasing drag. Consequently, the claim that the statement, namely, that increasing camber always enhances aerodynamic performance, is not universal but must be considered together with certain Reynolds numbers, angles of attack, freestream conditions, and airfoil geometries [2, 3].

3. Influence of camber variation on aerodynamic performance of NACA airfoils

The camber is among the critical geometric parameters that rule the aerodynamic load distribution of NACA airfoils, and its change does not only determine the lift in proximity to zero angle of attack but also changes the surface pressure distributions, boundary layer formation, flow separation, and stall mechanisms. Thus, the role of camber in the aerodynamic performance cannot be estimated via a mere lift coefficient but must be assessed based on various factors including lift, drag, lift-to-drag ratio, pitching moment and stall characteristics. Experimental data on classic NACA airfoils and later numerical data all demonstrate that camber variation may have a significant effect on the aerodynamic force properties of airfoils, but this effect is clearly dependent on the operating conditions [2].On fixed-camber airfoils, higher lift values can generally be achieved with less angle of attack when more positive camber is applied; on variable-camber airfoils, dynamic adjustment of camber allows the airfoil to respond to changing lift requirements and flight conditions, thus increasing the effective aerodynamic design region.

3.1. Effects on lift characteristics

Camber has the most direct impact on the lift characteristics. In the same thickness ratio and freestream conditions, a positive camber increase modifies the difference in velocities and pressures between the top and bottom surfaces of the airfoil so that the airfoil has positive lift at zero angle of attack and shifts the zero-lift angle of attack to the negative direction. Thus, in some finite interval

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of angles of attack, the lift curve tends to shift upwards overall as camber increases. This trend agrees with the fundamental result of thin airfoil theory which states that the most significant influence of camber on lift is due to its effect on the zero-lift angle of attack, but that the slope of the lift curve does not change by the same amount under ideal attached flow conditions.

Increasing the camber of an NACA four-digit airfoil as illustrated in Figure 1 causes the lift curve to shift upwards and the zero-angle of attack to move to the negative side, giving a greater lift coefficient on the same angle of attack.

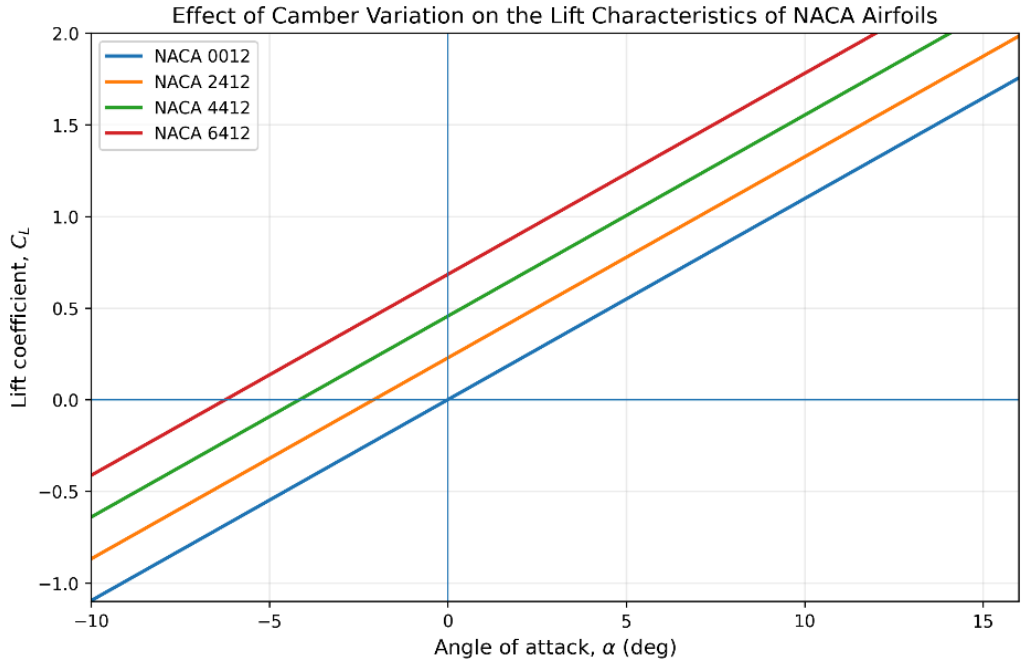

Figure 1. Theoretical influence of camber change on the lift behavior of NACA four-digit wing sections

In terms of real flow, camber variation has its effect not just in shifting the lift curve, but also changing chordwise pressure distribution. The low-pressure area on the upper surface of the airfoil may be increased by appropriately increasing camber, thus increasing the difference in pressure between the upper and lower surfaces, resulting in a greater lift coefficient at the same angle of attack. Historical research carried out by the NACA in low-speed wind tunnels compared a variety of airfoils with different cambers and found that the lift curve and the maximum lift coefficient are highly affected by camber variation, and that the stall characteristics also vary with camber [2].

Nevertheless, lift is not constantly increasing with the camber at every operating condition. In one situation, higher cambers might result in increased forward suction peaks and change the nature of the pressure recovery process, whereas, in another situation, strong adverse pressure gradients might lead to early separation of the boundary layer when the angle of attack is large enough, and the growth of lift starts to deviate slowly away from linearity. Thereby, the effect of camber on can be generally split into two steps: in low-to-moderate angle-of-attack region, it is mostly expressed as a higher lift value; once the angle of attack reaches the stall limit, the impact of flow separation becomes dominant, and at this stage, the effect of camber on maximum lift and stall angle of attack becomes more complicated.

The pattern is very important to the variable-camber airfoils. García Naranjo et al. examined how much camber magnitude and camber position of NACA four-digit airfoils could affect the

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aerodynamic performance of UAVs and noted that camber could be used as a significant design factor in modifying the levels of lift, and the optimal camber condition depends on the intended lift as well as the mission operating conditions [1]. The single-corrugated variable-camber experiment performed on NACA 0012 by Dhileep et al. also showed that as the necessary lift goes up, the correct camber deflection quantity varies too, which means that camber is not a fixed-performance parameter but can act as an active aerodynamic control parameter [4].

Consequently, in terms of lift, the dominant contribution of changing the camber is altering the lift bias and pressure-load distribution of the airfoil. When designing in practice, it would be wise to refrain from equating the concept of increasing camber with enhancing the ability to generate lift and instead consider the limits of maximum lift and stall, as well as target operating angles of attack.

3.2. Effects on drag characteristics

Contrary to lift, the influence of camber on drag is more complicated. Airfoil drag can be divided into two parts, namely skin friction drag and pressure drag, the size of which is determined by several factors, including boundary layer conditions, distribution of surface pressures, and extent of flow separation. However, the modification of camber does not guarantee the reduction in drag even when lift is enhanced.

At low to moderate angles of attack and with attached flow conditions, the correct addition of camber generally allows the desired lift to be obtained at a lower angle of attack, potentially reducing the geometric angle of attack necessary to provide the same lift demand. In such a manner, camber optimization could also be considered as a way to indirectly enhance aerodynamic efficiency. Nevertheless, in the fixed angle-of-attack comparison context, when camber increases suction peaks change together with pressure recovery processes, it might result in the intensification of local adverse pressure gradients and consequently, increase drag. Thus, the effect of camber on drag should be evaluated both in combination with two different evaluation methods, namely, the fixed angle of attack and fixed lift.

In the case of low-Reynolds-number flows, this discrepancy is even greater. At these conditions, the boundary layer is more susceptible to pressure gradient and transition position shift, and camber change could also change the size of the laminar zone, transition point and separation bubble behaviour, which results in high non-linearity of the drag values [5]. Experimental and computational analyses on NACA 0012 airfoils with morphing trailing edges have shown that various trailing-edge camber distributions have a significant impact on the pressure distribution, the wake structure, and the drag characteristics; those with larger trailing-edge cambers can obtain a higher lift without a substantial decrease in the overall lift-to-drag ratio [6].

It is important to remember that the influence of camber on drag is also very similar to the position of camber. When the maximum camber is focused near the leading-edge area, mid-chord, or trailing-edge zone, the resulting pressure gradient distribution will be different. Consider, for instance, that forward camber variation has a more pronounced effect on the suction peak, while trailing-edge camber variation has a larger impact on the posterior pressure recovery and trailing-edge loading. Consequently, when looking at various NACA airfoils, the magnitude of maximum camber alone cannot be used to determine the drag variations as the contribution of camber chordwise distribution is often ignored. Observing all other studies done in general, camber effect on drag usually implies a particular trade-off relationship: proper camber allows the airfoil to have a low drag rating at the target lift conditions, yet further increasing camber can lead to increased drag because of increased pressure gradients and increased separation. Thus, drag is not a separate

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parameter that is used to assess camber optimization, but should be taken into consideration along with target lift and operational mode.

3.3. Effects on Lift-to-drag ratio

Lift-to-drag ratio is an important indicator for comprehensively evaluating airfoil aerodynamic efficiency, defined as:

$$\frac{L}{D} = \frac{C_L}{C_D} \tag{15}$$

In comparison with studying the effects of either lift or drag alone, a lift-to-drag ratio can be more intuitively used to represent the overall aerodynamic advantages that camber variation offers. Hence, in practice (e.g., aircraft cruise and long-endurance UAV flight), lift-to-drag ratio is often a significant assessment factor of camber optimization.

At the low to moderate angles of attack, the lift coefficient typically increases when the positive camber is increased, however, the drag coefficient increase is comparatively small, thus possibly enhancing the lift coefficient. Research on NACA four-digit airfoils indicates that camber magnitude and location may be used as optimization parameters, and various camber states are associated with different optimal lift-to-drag ratio values. It shows that there is no one-size-fits-all optimal camber that can be applied to all situations irrespective of the particular operating conditions. The changes in the lift and drag coefficients of the NACA 2410 and NACA 8410 airfoils versus angle of attack are depicted in Figure 2. The contrast of the lift and drag coefficients between the NACA 2410, NACA 8410 and transition NACA 2410-NACA 8410 profiles is provided in Figure 3 [3].

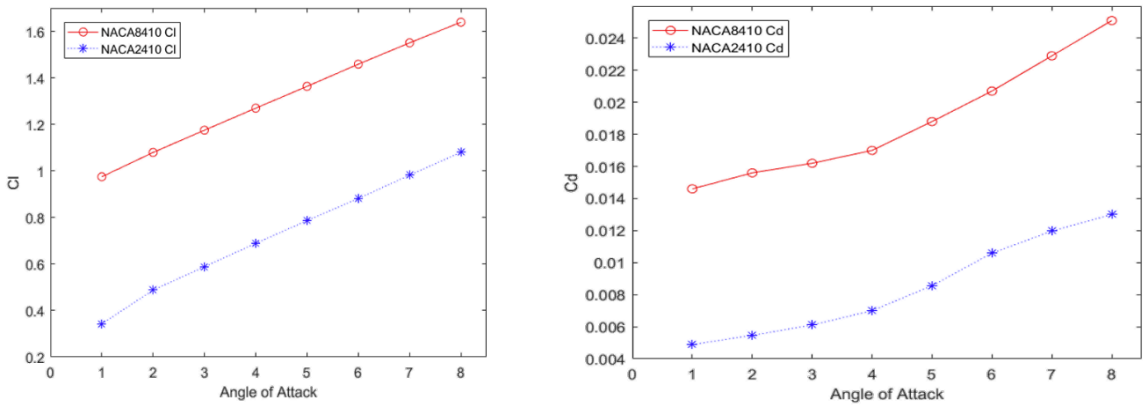

Figure 2. NACA2410 and NACA8410 with changing AoA [3]

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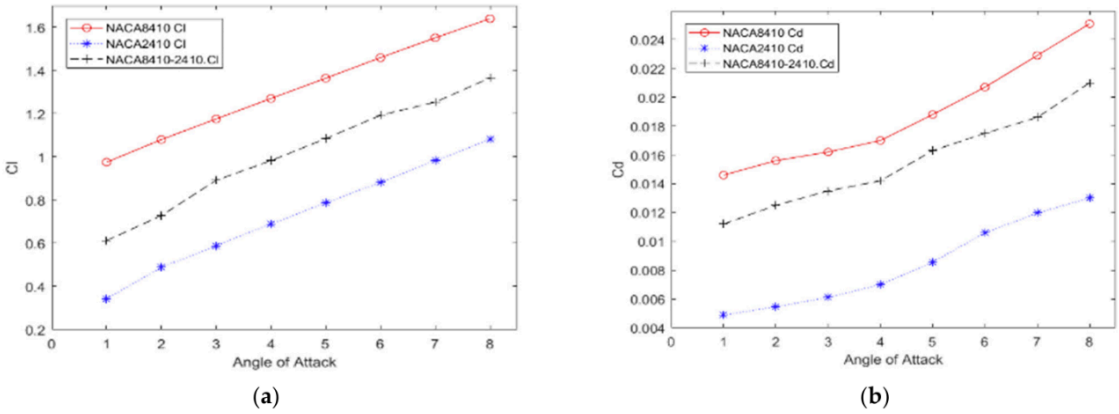

Figure 3. (a) CL, (b) CD of NACA2410, NACA8410, and NACA2410 to NACA8410 transition with respect to AoA [3]

It is important that the camber associated with the highest lift-to-drag ratio is not necessarily the same as the camber associated with the highest lift. Increased Camber (larger cambers) can produce more lift at lower angles of attack, but they could also have increased pressure gradients and drag. Hence, in the case where the optimization goal switches between maximizing lift and maximizing lift-to-drag ratio the ideal camber changes. The discrepancy indicates that the issue of camber optimization is inherently multi-objective aerodynamic optimization problem.

The variable camber is another example of this feature in research. Fincham and Friswell suggested that the whole physical variable-camber mechanism should be included in the aerodynamic optimization process; studies indicated that the variable-camber airfoils that are able to adjust to various flight conditions have the ability to enhance multi-condition aerodynamics over the fixed-shape airfoils [7,8]. The major benefit of variable-camber design over conventional fixed-camber airfoils is neither the endless boost of lift-to-drag ratio at a given operating state, but changing the shape of airfoils depending on several flight regimes to get a more practical match between aerodynamic efficiency at different operating conditions.

Thus, based on the lift-to-drag ratio, camber optimization involves taking into account the target lift, angle of attack and the flow states at the same time. In the case of fixed-camber airfoils, the emphasis is placed upon finding out what camber will be appropriate under primary operating conditions; in the case of variable-camber airfoils, camber may be additionally used as a control variable that changes with the operating conditions, thus achieving optimization of multi-state aerodynamic performance.

3.4. Effects on pitching moment

The variation in camber affects not just the lift and drag characteristics, but also exerts a substantial effect on the pitching moment of the airfoil. Since the camber changes the pressure distribution on the upper and lower surfaces as well as the chordwise load distribution, the location of the resultant aerodynamic force will change, resulting in corresponding changes of the pitching moment coefficient of the airfoil.

In case of conventional positive-camber airfoils, the aerodynamic loads generally tend to focus on the front part of the airfoil which makes the pitching moment at quarter chord length to be more

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negatively inclined. If there is an increase in the camber, fluctuations in the pressure distribution become more significant, and the pitching moment also varies. Thus, the quest to achieve high lift or high lift-to-drag ratio only could impose extra trimming load and structural loads.

The early NACA experimental studies combined lift, drag and pitching moment with chordwise pressure distribution in their analysis, showing that aerodynamic changes due to camber variation have unique holism and that lift changes cannot be totally disassociated with moment changes. Moment variations caused by camber changes are also of great significance in aircraft with precise attitude control since they can affect trim drag and the operational requirements of the control system.

Variable-camber airfoils studies also suggest that by carefully designing the region where the camber changes, it is possible to change the pitching moment without altering the lift. Wu et al. came up with an idea of an airfoil with an active trailing-edge morphing system able to provide multi-degree-of-freedom control of aerodynamics, and they stated that various deformation modes may result in a specific level of decoupling of lift and pitching moment, increasing the effective control envelope of the airfoil [9]. It is shown that, unlike conventional rigid airfoils, variable-camber technology is not simply a way to improve lift or lift-to-drag ratio, but can be extended to become an active form of aerodynamic load control.

Consequently, in the process of optimizing cambers, (C_M) ought to be an inalienable constraint or a measure of assessment. In particular, in the case of future variable-camber airplanes, all of the coupled relationships between the lift control, the drag level, and the pitch-moment need to be taken into account at the same time to avoid the possibility of localized performance improvements leading to overall flight performance decline.

3.5. Effects on stall characteristics

Stall is a significant contributor to limiting the high-angle-of-attack aerodynamic behavior of airfoils, and its physical significance has much in common with boundary layer separation and recovery of pressure processes. The change in camber redistributes the pressure gradients on the surface of the airfoil and changes the location of flow separation initiation, the size of the separation region, and the final stall configuration.

Appropriate camber within moderate angles of attack will increase the lift coefficient of an airfoil and enable the necessary lift to be achieved at a smaller geometric angle of attack, however, it does not mean that stall performance will be better. The continued growth of the angle of attack would cause localized pressure peaks and negative pressure gradients caused by camber which would make the boundary layer more prone to separation. This is the point where the effect of camber on and is based on particular camber distributions, thickness distributions, and Reynolds numbers.

Old NACA experimental studies revealed that stall properties are highly dependent on camber as they have been found to have different flow separation patterns at various camber conditions [2] This shows that stall cannot be reduced to a monotonic relationship between larger camber and higher maximum lift. Especially in high-angle-of-attack cases, pressure-recovery ability at the surface and anti-separation properties of the boundary layer can be much more significant than low-angle-of-attack increases in lift. The experimental and numerical findings obtained at NACA 0012 airfoils with continuous morphing trailing edge suggest that, under some conditions, increasing the camber of the trailing edge can not only raise the lift but also change the separation structure of the trailing edge and even postpone partial separation of the flow at larger angles of attack [6]. This has shown that the role of camber cannot be explained merely through the highest camber value; the

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point of camber change, the length of deformation region, and particular curvatures of upper and lower surfaces are just as essential.

One major benefit of variable-camber airfoils is actually their ability to change camber based on the present operating conditions, applying greater camber when high lift is needed and lesser camber in low-drag cruise flight regime. Dhileep et al. studies on NACA 0012 variable-camber airfoils indicated a direct relationship between the optimum deformation state and the targeted lift, and that there is a deformation state at a given angle of attack which would allow aerodynamic efficiency to achieve greater values [4]. It suggests that variable-camber technology has the potential to dynamically balance between the requirements of lift and stall margins [10].

On average, the influence of camber variation on stall characteristics is more non-linear than on low-angle-of-attack lift characteristics. Fixed-camber airfoils need to have a rationally matched camber magnitude and camber position to prevent undesirably high adverse pressure gradients; variable-camber airfoils can be continuously adjusted to regulate the stall characteristics under the operating conditions. The future optimization studies based on camber should thus combine both stall angle of attack, and separation position in addition to lift-to-drag ratio and pitching moment instead of optimizing with a single performance indicator.

4. Flow mechanism of how camber variation affects aerodynamic performance

The variation in airfoil camber has an impact on aerodynamic performance through changes in pressure distributions and flow separation behaviour. A positive camber produces a larger drop in pressure at the front which moves the center of lift forward and increases lift, and at the same time, smooth curvature deformation eliminates geometric discontinuity and hence delays flow separation. It was indicated by Dhileep et al. that compared to the conventional flaps, continuous camber-variation arc reduces flow detachment phenomena and thus results in higher lift-to-drag ratio than stepped flaps.

The mechanism suggested by Ozbek et al. is Rear Spar Articulated Wing Camber (RSAWC), which uses a rib configuration similar to a fishbone structure along with rear-spar articulation to obtain continuous camber morphing. Wind-tunnel tests demonstrated that under zero-angle-of-attack cruise conditions, unflapped, there was a 15.2 percent improvement in lift-to-drag ratio, whereas semi-empirical flight-test analysis demonstrated a cruise flight time increase of roughly 18.75 percent with respect to the conventional wing [11]. However, wind tunnel measurements and CFD analysis demonstrate that high angles of attack are more likely to create attached boundary layer stratification across smooth areas, and have higher flow stability; low angles of attack also increase the camber, which increases the forward low pressure, creating further lift.

Generally speaking, camber adjustment is a continuously adjustable type of lift regulation, and its outcomes are obtained by redistributing forward and aft pressure distributions and delaying their separation, which is smoother and more efficient in terms of energy compared to the conventional discrete control surfaces (flaps). The current section explains the effect that changing the camber has on the lift-to-drag performance of an aircraft based on the understanding of fluid mechanics, both in terms of the physical phenomena of the alteration of flow fields at different cambers, as well as numerical and experimental findings.

5. Conclusions

The paper discussed how the camber variation affected the aerodynamic performance of NACA airfoils. Positive camber increase has a tendency to increase the lift of a given angle of attack and

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move the zero-lift angle of attack in the negative direction. Nevertheless, it has different consequences on drag, lift-to-drag ratio, pitching moment, and stall characteristics based on such parameters as camber distribution, angle of attack, Reynolds number, and flow state. Too much camber might enhance negative pressure gradients and cause flow separation causing reduced aerodynamic efficiency. In general, camber needs to be optimized based on particular operation conditions and performance goals, with the variable-camber technology offering a good solution to the adaptive aerodynamic control.

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