

Aerodynamic Performance Optimization of NACA 2412 Aerofoil by Morphing Concept using CFD

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Article Info	ABSTRACT
Article History: Submitted: November 16, 2025 Revised: May 4, 2026 Accepted: August, 31	<i>This study is a continuation of previous research, with a special discussion on optimizing the aerodynamics of the NACA 2412 aerofoil by applying the morphing concept. The morphing aerofoil concept was selected because it can change shape as required, offering the potential for significant improvements in aerodynamic performance. This study focuses on optimizing the morphing aerofoil shape to achieve the maximum lift to drag ratio (Cl/Cd) in each change of angle of attack. A Computational Fluid Dynamics (CFD) approach was used to simulate variations in speed and angle of attack to identify the most aerodynamically efficient morphing aerofoil configuration. The results of this study are expected to contribute to the development of morphing aerof. 2026oil designs that not only improve aerodynamic efficiency but also refine the concept design stage, so that the aerofoil is expected to be ideal and superior in its class. Overall, the simulation results show an aerodynamic performance that is in accordance with the theoretical expectations for the aerofoil configuration with a morphing NACA 2412 aerofoil. The morphing concept applied to the 2D airfoil section showed that its aerodynamic effectiveness strongly depends on the flight conditions, particularly the angle of attack. At 0° AoA, morphing the aft 30% of the chord provided a substantial aerodynamic benefit, boosting lift from $Cl = 0.1990$ to $Cl = 1.3178$ and improving Cl/Cd from 21.43 to 47.75, yielding a 122.76% increase. This is clearly reflected in the static pressure contours, where the morph-induced curvature strengthened the suction on the upper surface without causing large drag penalties. However, at higher AoAs (4°, 8°, and 12°), the morphing effect became progressively less efficient. Although the lift continues to increase after morphing, the drag increases at a much faster rate owing to stronger adverse pressure gradients and an earlier onset of pressure recovery distortion. As shown in the pressure contours, the altered aft section created additional pressure buildup near the trailing edge, causing a higher profile drag. Consequently, Cl/Cd decreased by 11.12%, 28.61%, and 13.26% at 4°, 8°, and 12°, respectively.</i>
Keywords: Morphing Aerofoil, NACA 2412, CFD, Aerodynamic Optimization	

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INTRODUCTION

Efforts to achieve higher aerodynamic efficiency remain a fundamental principle in the design of modern aircraft. One such approach is the application of morphing aerofoil technology, which is characterized by the ability to dynamically alter the aerofoil geometry in response to varying flight conditions. This represents a transformative advancement in aerospace engineering, particularly in the development of future aircraft aerofoils. This technology enables significant improvements in operational performance, including enhanced fuel efficiency, extended flight range, and superior maneuverability [1]. Among the various morphing aerofoil technologies, modifications to the trailing edge have particularly profound effects. The trailing edge serves as a critical zone for controlling aerodynamic forces, particularly lift and drag. Conventional aerofoil control surfaces (including flaps and ailerons) often face challenges related to mechanical complexity and energy inefficiency [2]. In contrast, morphing aerofoil trailing edges provide an adaptive and effective approach to enhancing aerodynamic performance by enabling smooth and optimal geometric transitions [3], [4].

To address these challenges, Aerodynamic Shape Optimization (ASO) has emerged as a powerful tool. By employing computational methods, the ASO determines the optimal geometries that minimize drag while maximizing the lift-to-drag ratio. This approach integrates seamlessly with advanced Computational Fluid Dynamics (CFD) simulations and detailed evaluations of the morphing configurations of the airfoil under various operational scenarios [5]. CFD simulations facilitate an in-depth analysis of airflow phenomena around the morphing trailing edge by capturing critical aspects such as boundary layer behavior, flow separation, and vortex formation. Advanced optimization algorithms, including Genetic Algorithms (GA) and adjoint-based methods, further enhance the exploration of design parameters. Key parameters, such as the deflection angle, camber distribution, and trailing edge thickness, can be iteratively refined to achieve superior aerodynamic performance [6][7].

Structural and material constraints add another layer of complexity to the development of morphing aerofoils. Ensuring compatibility between aerodynamic efficiency and structural integrity is essential, and lightweight materials and energy-efficient mechanisms are critical. Therefore, the interaction between aerodynamic loads and structural deformation becomes a central consideration, guiding the development of practical and effective morphing solutions [8].

This study investigates the application of morphing aerofoil technology to the NACA 2412 aerofoil to enhance aerodynamic efficiency, reduce energy consumption, and expand operational capabilities, contributing to sustainable aviation technology. The primary objective of this study was to analyze the aerodynamic optimization of a morphing wing based on the NACA 2412 aerofoil. Specifically, this study investigated the influence of optimized morphing geometry at angles of attack of 0° , 4° , 8° , and 12° on the achievement of optimal aerodynamic performance. It further seeks to determine the lift-to-drag ratios (CL/CD) at these conditions and evaluate their effectiveness in improving aerodynamic efficiency. Finally, this study aims to develop an optimized three-dimensional wing geometry using the NACA 2412 aerofoil and assess its aerodynamic performance for application in aircraft.

This study focuses exclusively on the aerodynamic optimization of a morphing aerofoil configuration using Computational Fluid Dynamics (CFD). The NACA 2412 airfoil was employed as the baseline model, with geometric modifications restricted to the region between the maximum camber point and the trailing edge. Numerical simulations were performed using ANSYS Fluent without physical or experimental testing. The study examined four angles of attack — 0° , 4° , 8° , and 12° — at a Reynolds number of 2.2×10^6 under sea-level standard atmospheric conditions (ISA+0). Optimization efforts are limited to improving aerodynamic performance in terms of the lift-to-drag ratio (CL/Cd), while moment coefficients, structural considerations, and other parameters are excluded from the scope.

METHODS

This study examined how changing the shape of wings can improve their performance in the air. These wings, called morphing wings, can adjust to different flight conditions to improve performance. The NACA 2412 airfoil was used as a model because it is well known and often used in studies. The research was conducted in steps to ensure that everything was covered. First, it examines the problems with wings that do not change shape and how morphing wings can be improved by

improving lift-to-drag ratios [9], [10], [11]. The study aims to determine the best wing shapes for different flight stages to save fuel and improve control [12]. A detailed review of past studies on morphing wings, optimization methods, and CFD (computational fluid dynamics) applications was done [13]. This includes examining how wings bend, shape optimization, and past CFD tests of the NACA 2412 aerofoil [14], [15], [16]. The review found that certain optimization methods were not sufficiently used, and there was not enough testing against real wind tunnel data [17], [18], [19].

Simulations were performed using ANSYS Fluent Student software to analyze the aerodynamic parameters. The setup involved careful model preparation and testing to improve the lift-to-drag ratio [20]. The results were compared with NASA wind tunnel data to ensure accuracy [21]. The optimization focused on changing the aerofoil shape from the middle to the back while maintaining the front shape to maintain airflow [22]. The method used allows efficient updates to improve performance. This process deals with the trade-offs in morphing wing designs and follows the previous optimization methods. The optimized NACA 2412 profile was then applied to a 3D wing model for future research. This phase examines the overall performance of the wing, considering important factors for practical use. The final phase involved a detailed evaluation of the results, including the aerodynamic coefficients and flow visualization. Validation against parametric computation data confirmed that the optimized 2D airfoil met the goals and advanced adaptive wing technologies. This study discusses future designs and their integration with control systems [23]. This method fills existing gaps by combining optimization with thorough validation, providing a framework for improving the aerodynamics of morphing wings.

Benchmark Analysis

Figure 1 presents the static pressure distribution around the baseline NACA 2412 airfoil at zero angle of attack, which was obtained from the validated CFD setup. The contour visualization demonstrates a physically consistent pressure gradient, where a pronounced low-pressure region is formed over the suction surface near the leading edge, whereas a corresponding high-pressure zone develops on the pressure side. This pressure differential aligns well with the classical aerodynamic theory for cambered airfoils at zero incidence, confirming that the flow accelerates over the upper surface owing to the geometric curvature, thereby generating lift even without a positive angle of attack. The mesh distribution shown in the figure highlights the use of a sufficiently refined grid near the airfoil boundary, enabling an accurate resolution of the pressure gradients and boundary layer phenomena. The coherence of the pressure field, absence of unphysical oscillations, and smooth propagation of pressure contours into the far field collectively demonstrated that the computational domain size, boundary conditions, and numerical schemes employed in this study were well-posed and stable. Thus, Figure 1 serves as a qualitative foundation, ensuring that the CFD environment is capable of reproducing realistic aerodynamic behaviors prior to quantitative benchmarking.

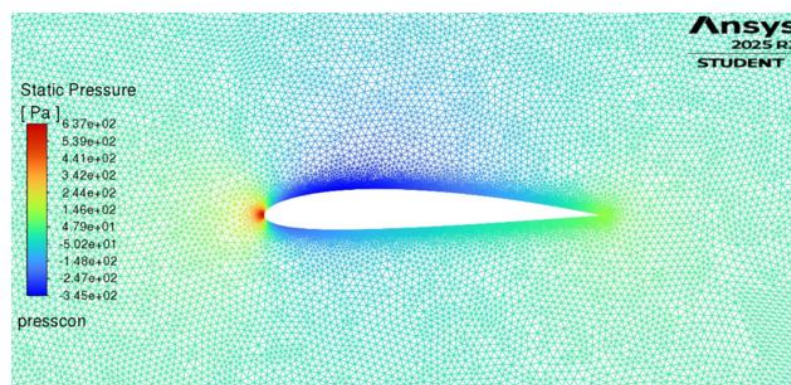


Figure 1 NACA 2412 standard shape and zero angle of attack

Figure 2 further strengthens the validation by comparing the numerical predictions of lift and drag characteristics with high-quality experimental data at a representative Reynolds number of $Re = 2.2 \times 10^6$. In Figure 2(a), the lift curve slope ($C_l - \alpha$) shows excellent agreement between the CFD and experimental results across a wide range of angles of attack. Both datasets captured the linear region,

onset of nonlinearity, and stall peak near 14° with remarkable consistency. The close alignment indicates that the turbulence model and mesh strategy accurately captured the boundary layer behavior and flow separation onset. Figure 2(b) presents the drag polar (C_l - C_d), in which the CFD results display slightly higher drag values than the experimental data, particularly at higher lift coefficients. This systematic overprediction is typical in RANS-based simulations owing to the increased sensitivity to near-wall turbulence modeling and laminar-turbulent transition assumptions. Nonetheless, the overall shape and curvature of the drag polar remained consistent with the experimental trends, demonstrating that the computational model successfully reproduced the aerodynamic performance envelope of the airfoil.

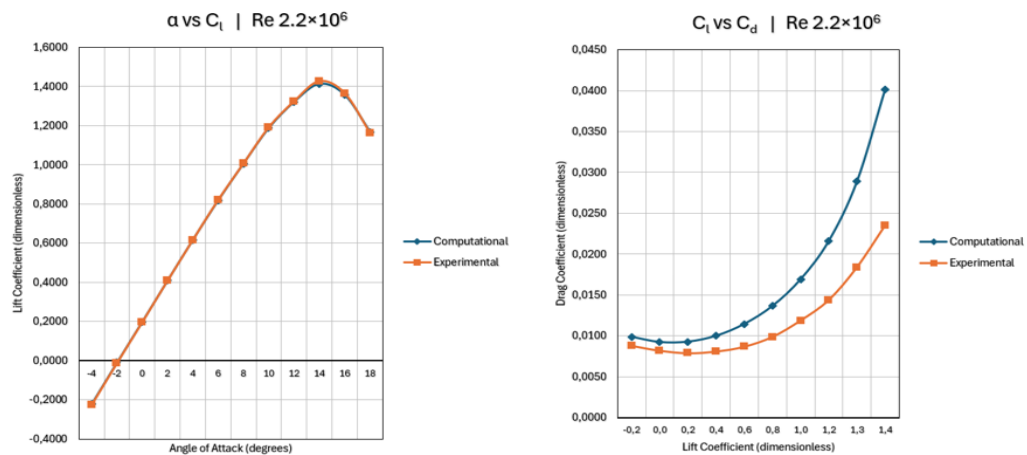


Figure 2 C_L vs AOA and C_L vs C_D as benchmark

Table 1 provides a quantitative assessment of the benchmarking accuracy by tabulating the C_L and C_D values from both the CFD and experimental measurements across the investigated range of angles of attack. The comparison revealed a high level of fidelity, as reflected by the relatively small error percentages for most operating conditions. The computational lift coefficient matched the experimental measurements with deviations typically below 1%, except at very low angles of attack, where the measurement uncertainties and numerical sensitivities were inherently higher. The drag coefficient, although slightly over-predicted, exhibited consistent trends that remained within a reasonable error range for the RANS-based CFD framework. The overall average error of 2.1486% demonstrates that the numerical model is robust and sufficiently accurate to support further parametric studies and optimization (Table 1). This benchmark table thus provides quantitative confirmation that the chosen domain size, grid resolution, and solver settings can reliably capture aerodynamic forces, establishing the credibility required for the subsequent analyses presented in this study.

Table 1 C_L vs AoA and C_L VS C_D as benchmark

BENCHMARK					
AoA	Computational		Experimental		Error
	C_l	C_d	C_l	C_d	
-4	-0,2209	0,0099	-0,2250	0,0088	1,8417
-2	-0,0095	0,0092	-0,0119	0,0082	19,9706
0	0,1990	0,0093	0,1975	0,0079	0,7759
2	0,4097	0,0100	0,4095	0,0081	0,0552
4	0,6174	0,0115	0,6175	0,0087	0,0089
6	0,8192	0,0137	0,8215	0,0099	0,2793
8	1,0068	0,0169	1,0075	0,0119	0,0646
10	1,1881	0,0216	1,1925	0,0144	0,3686
12	1,3211	0,0289	1,3250	0,0184	0,2907
14	1,4129	0,0401	1,4275	0,0235	1,0228
16	1,3562	0,0616	1,3650	0,0187	0,6473
18	1,1678	0,1051	1,1625	0,0124	0,4577
Average Error					2,1486

Gradient-Based Optimization Framework Applied to the Trailing Edge of NACA 2412 Airfoil

The gradient-based optimization method provides a computationally efficient and rapidly convergent framework for refining complex airfoil geometries, particularly in localized regions such as the trailing edge [24]. Unlike global optimization algorithms, which require extensive sampling across a high-dimensional design space, the gradient-based approach exploits the sensitivity of aerodynamic performance metrics to small geometric perturbations. The optimization problem can be expressed as the minimization of an objective function $J(X)$ representing aerodynamic performance parameters, such as drag coefficient C_D or lift-to-drag ratio C_L/C_D with following equation (1).

$$\min_x J(X) = \min_x f(C_L(X), C_D(X)) \quad (1)$$

$$R(U, x) = 0 \quad (2)$$

where x denotes the design variable vector controlling the airfoil geometry specifically the local curvature and thickness distribution at the trailing edge, and U represents the vector of conservative flow variables as show in Fig. 4 below. The sensitivity of the objective function with respect to each design variable, $\partial J/\partial x$, is determined through adjoint-based differentiation or finite-difference perturbation [25], [26]. The iterative update of the design parameters follows the general form:

$$x^{(k+1)} = x^k - \alpha^k \nabla J(x^k) \quad (3)$$

where α^k is the adaptive step size obtained from a line-search or trust-region strategy. Convergence is achieved when the Euclidean norm of the gradient satisfies $\|\nabla J\| < \epsilon$, where ϵ is a specified tolerance level.

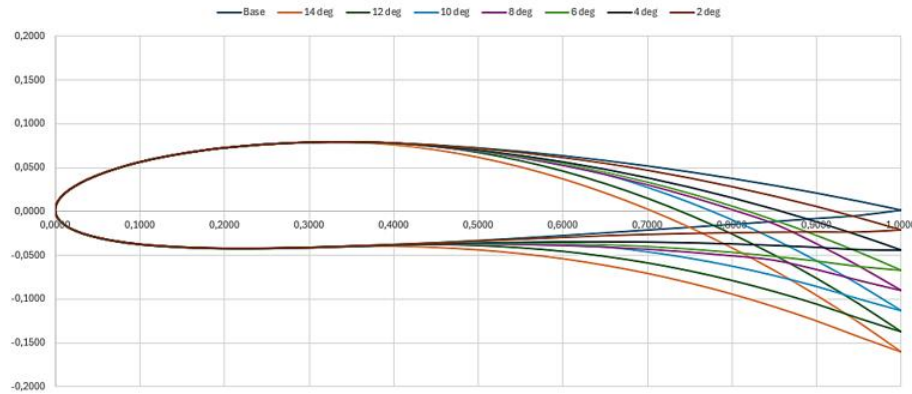


Figure 3 NACA 2412 shape changes by morphing concept

This mathematical framework enables highly localized control of the airfoil geometry, allowing engineers to fine-tune the trailing edge without compromising other aerodynamic characteristics shown in Figure 3. The trailing edge is particularly critical for managing the boundary layer separation, pressure recovery, and wake dynamics. Consequently, gradient-based refinement in this region can significantly improve the lift-to-drag ratio C_L/C_D , delay stall onset, and reduce the overall pressure drag under cruise conditions. The integration of this optimization technique into computational fluid dynamics (CFD) workflows enables fully automated, iterative processes. Each design cycle involves CFD solution convergence, gradient computation, and design variable updating, facilitating continuous geometric refinement until an optimal configuration is achieved. This coupling between CFD and optimization routines enhances the design efficiency and reduces the computational costs, schematically in Fig. 5. Moreover, the gradient-based framework can be readily extended to multi-objective optimization scenarios in which multiple aerodynamic and structural performance metrics are considered simultaneously [27], [28]. The general form of the objective function is as follows:

$$J = w_1 C_D - w_2 C_L + w_3 \sigma + w_4 N \quad (4)$$

where w_1 , w_2 , w_3 , and w_4 are weighting coefficients corresponding to drag C_D , lift C_L , structural stress σ , and acoustic noise level N . This formulation enables the development of optimized airfoil geometries that balance aerodynamic efficiency, structural integrity, and noise mitigation objectives, which are essential for modern aircraft design.

In summary, the gradient-based optimization method, when applied to the trailing edge of the NACA 2412 airfoil, demonstrated strong potential for improving the aerodynamic performance through mathematically guided and computationally efficient geometric refinement. Its ability to integrate seamlessly (Figure 4) with CFD solvers, manage multi-objective trade-offs, and converge rapidly toward optimal solutions renders it a robust tool for advanced aerodynamic shape optimization and morphing wing design applications.

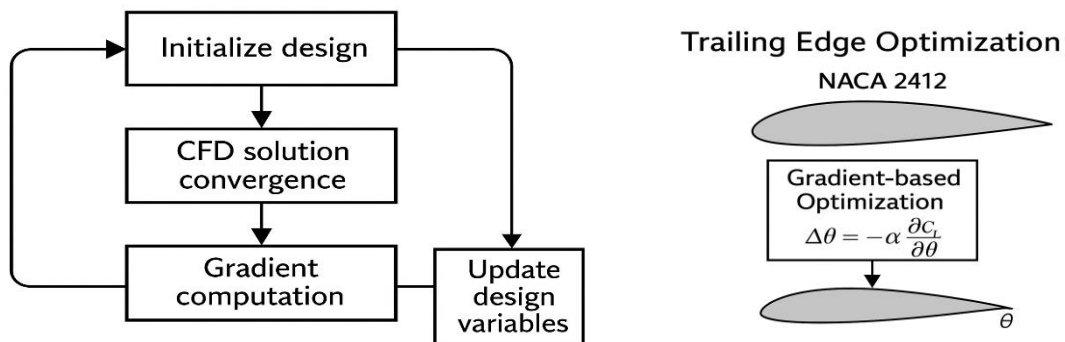


Figure 4 Schematic of Trailing Edge NACA 2412 optimization process

Result and Discussion

Morphing was performed by altering the airfoil surface from the maximum camber location to the trailing edge ($0.3c \rightarrow TE$). This aft-localized deformation acts similarly to a cambered flap: it increases the aft camber and suction, raising lift; however, it also increases pressure/viscous drag by enlarging the effective wake and strengthening adverse pressure gradients downstream of the hinge. The static pressure contour pairs (baseline vs. morph) corroborate these mechanisms for each AoA.;

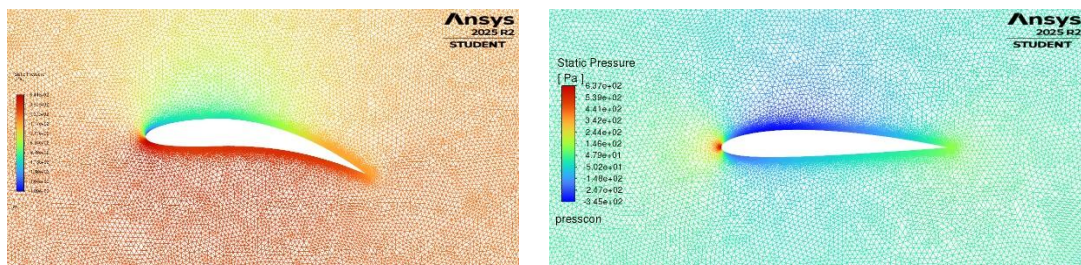


Figure 5 0 degrees AoA with 14 degrees morphing deflection from 0.3C

At 0° AoA, the morphing deflection from 0.3c generates a very large aerodynamic efficiency gain, with the baseline airfoil producing $C_l = 0.1990$, $C_d = 0.0093$, and $C_l/C_d = 21.43$, whereas the morphed configuration increases these values to $C_l = 1.3178$, $C_d = 0.0276$, and $C_l/C_d = 47.75$, resulting in a +122.76% improvement in efficiency shown in Figure 5. The static pressure contours clearly illustrate this. The baseline case exhibited only mild suction over the upper surface, whereas the morphed geometry produced a significantly stronger and more extended suction region, particularly near the aft upper surface, without triggering a significant separation. The increased aft camber acts similarly

to a low-deflection flap, dramatically boosting the lift while keeping the flow largely attached. Although drag increases, the relative lift gain far outweighs the drag penalty, yielding a major improvement in the C_l/C_d . This case demonstrates that at low AoAs, aft morphing is highly effective because the flow remains clean and receptive to additional camber.

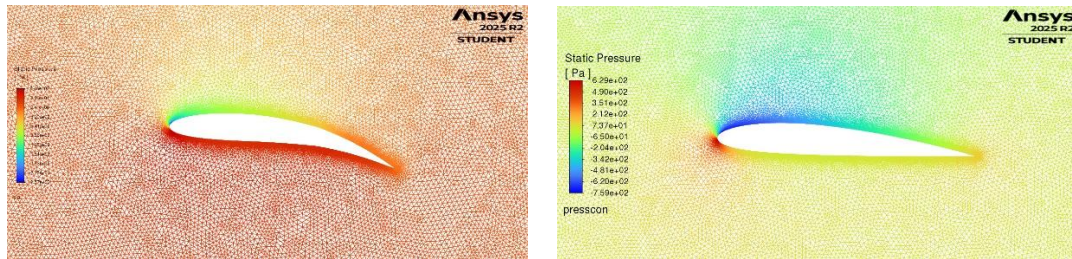


Figure 5 4 degrees AoA with 10 degrees morphing deflection from 0.3C

At 4° AoA, morphing increased lift but caused the aerodynamic efficiency to deteriorate, with the baseline values of $C_l = 0.6174$, $C_d = 0.0115$, and $C_l/C_d = 53.88$ shifting to $C_l = 1.4269$, $C_d = 0.0298$, and $C_l/C_d = 47.88$, yielding an -11.12% reduction in efficiency shown in Figure 5. The static pressure contours show that although the morphed aerofoil still produces a pronounced suction peak on the upper surface, the aft deflection introduces a stronger adverse pressure gradient and a visibly thicker low-pressure wake region behind the trailing edge compared to the baseline. This indicates the onset of mild separation or increased wake losses that increased drag more than the additional suction increased lift. Thus, unlike the 0° case, the increased aft camber at 4° AoA amplified the drag disproportionately, reducing the overall aerodynamic efficiency, even though the lift continued to rise.

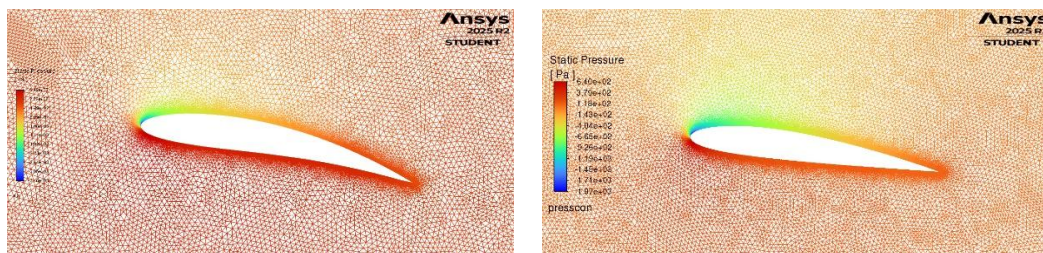


Figure 6 8 degrees AoA with 6 degrees morphing deflection from 0.3C

At 8° AoA, morphing again increases lift but significantly worsens C_l/C_d , where the baseline $C_l = 1.0068$, $C_d = 0.0169$, and $C_l/C_d = 59.48$ degrade to $C_l = 1.5244$, $C_d = 0.0359$, and $C_l/C_d = 42.46$, producing a -28.61% reduction in efficiency shown in Figure 6. This behavior was supported by the pressure contours. In the baseline case, the flow remained relatively attached despite the higher AoA; however, in the morphing case, the aft camber increase forced the pressure recovery to occur more abruptly, creating a larger separated region and visibly thicker wake, as shown by the extended low-pressure zone behind the trailing edge. At this moderate-high AoA, the boundary layer is already sensitive, and the morphing deformation magnifies the pressure drag and wake losses, causing the drag increase to dominate the lift benefit. Consequently, the efficiency decreased sharply, indicating that morphing became increasingly counterproductive as the AoA increased.

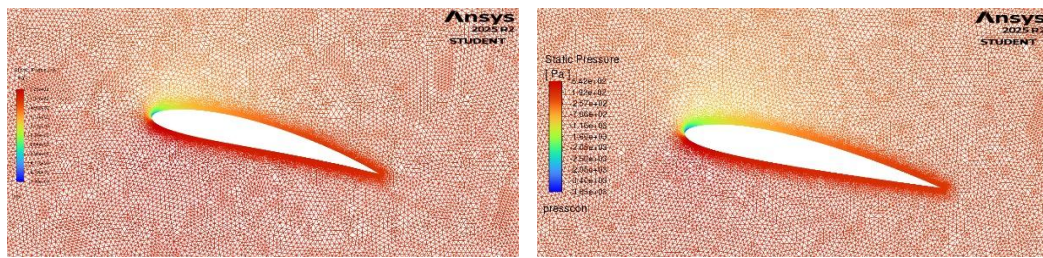


Figure 7. 12 degrees AoA with 3 degrees morphing deflection from 0.3C

At 12° AoA, the airfoil approached a near-stall regime, and the morphing effect showed the smallest improvement in lift, but still resulted in a net loss in aerodynamic efficiency. The baseline airfoil yielded $C_L = 1.3211$, $C_D = 0.0289$, and $C_L / C_D = 45.75$, while the morphed configuration yielded $C_L = 1.5812$, $C_D = 0.0399$, and $C_L / C_D = 39.68$, resulting in a 13.26% efficiency reduction shown in Figure 7. The static pressure contours revealed that the baseline exhibited strong suction near the leading edge and a region of separation development toward the aft surface. However, the morphed airfoil intensified the adverse pressure gradient, causing earlier or larger separation and a noticeably broader wake. This drives the drag higher at a faster rate than the lift can increase. At such a high AoA, the flow is dominated by separation physics rather than camber-driven lift gains; therefore, aft morphing increases losses rather than improving performance.

CONCLUSIONS

The morphing concept applied to the 2D airfoil section showed that its aerodynamic effectiveness strongly depends on the flight conditions, particularly the angle of attack. At 0° AoA, morphing the aft 30% of the chord provided a substantial aerodynamic benefit, boosting lift from $C_l = 0.1990$ to $C_l = 1.3178$ and improving C_l/C_d from 21.43 to 47.75, yielding a 122.76% increase. This is clearly reflected in the static pressure contours, where the morph-induced curvature strengthened the suction on the upper surface without causing large drag penalties. However, at higher AoAs (4°, 8°, and 12°), the morphing effect became progressively less efficient. Although the lift continues to increase after morphing, the drag increases at a much faster rate owing to stronger adverse pressure gradients and an earlier onset of pressure recovery distortion. As shown in the pressure contours, the altered aft section created additional pressure buildup near the trailing edge, causing a higher profile drag. Consequently, C_l/C_d decreased by 11.12%, 28.61%, and 13.26% at 4°, 8°, and 12°, respectively shown in Table 2.

Table 2. Comparison between base and morphing for NACA 2412 aerofoil

AoA	Base			Morphing			Improve (%)
	C_l	C_d	C_l/C_d	C_l	C_d	C_l/C_d	
0	0.1990	0.0093	21.4341	1.3178	0.0276	47.7464	122.76
4	0.6174	0.0115	53.8758	1.4269	0.0298	47.8826	-11.12
8	1.0068	0.0169	59.4829	1.5244	0.0359	42.4624	-28.61
12	1.3211	0.0289	45.7453	1.5812	0.0399	39.6788	-13.26

This behavior contrasts with traditional flap deflection, where the aerodynamic platform is extended downward to increase the effective camber efficiently at elevated lift demands. Morphing, in the configuration of this study, continuously changes the physical geometry, but becomes less advantageous at higher AoAs, where the baseline airfoil is already producing a high lift and the dominant effect of morphing is drag growth. Thus, morphing is highly beneficial at low AoAs but less suitable for high-lift conditions without additional shape optimization.

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