

# Numerical Investigation of a NACA 0012 Airfoil with Static-Extended Trailing Edges and Gurney Flaps for Low-Reynolds-Number Wind Turbine Applications

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**Abstract** The efficiency of a wind turbine depends on the aerodynamic efficiency of its blade's airfoil geometry. In this study, we numerically investigate the influence of static extended trailing edges (SETEs) and gurney flaps (GFs) on the aerodynamic characteristics of the NACA 0012 airfoil at a low Reynolds number ( $Re = 2 \times 10^5$ ). The analysis was conducted using computational fluid dynamics (CFD) based on the 2-dimensional steady and unsteady Reynolds-Averaged Navier-Stokes (RANS/URANS) with the  $k-\omega$  Shear Stress Transport (SST) model. Three different-sized SETE flap lengths of 10%c, 20%c, and 30%c and three Gurney flaps with heights of 1%c, 2%c, and 3%c were tested at various angles of attack ( $-4^\circ$  to  $20^\circ$ ). Measurements used the same baseline airfoil at the same Reynolds number to ensure direct comparison between SETE and Gurney flaps. Results show that while the GF 2%c produces high lift, it also causes greater instability beyond stall. SETE 20%c provides superior lift-to-drag ratios, delays separation, and reduces unsteady wake structures, making it an ideal configuration for small-scale wind turbine applications.

**Keywords:** NACA0012, Gurney flap, Static extended trailing edge, CFD, low Reynolds number

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## 1. Introduction

An airfoil is the shape of a wind turbine blade's cross-section that creates aerodynamic force when moving through the air. Airfoils produce lift, control drag, and influence a wind turbine's overall aerodynamic performance [1,2].

Unlike Horizontal Axis Wind Turbines (HAWTs), whose blades move through relatively steady and uniform airflow, Vertical Axis Wind Turbines (VAWTs) face a unique challenge of encountering wind that's constantly changing direction due to the turbine's rotation. This unsteady environment causes flow curvature, a phenomenon where the air flow bends around the rotating blades, resulting in fluctuations in pressure and velocity distribution along the blade surface [3]. Another significant challenge is the cyclical change in the angle of attack (AoA). As the blades rotate, they continuously experience shifting AoA, some of which can become excessively high, leading to early flow separation. This results in a sharp increase in drag and a corresponding decrease in aerodynamic efficiency [4,5].

To address these challenges, various strategies have been proposed, including modifications to airfoil design and the implementation of active control mechanisms. For

instance, thicker airfoil profiles are more resilient to pressure and flow changes, allowing them to handle higher pressure loads. Twisting the blade geometry can help maintain a favorable AoA throughout the rotation, improving performance, and leveraging computational fluid dynamics (CFD) simulations. Over the past four decades, researchers have relied on CFD as a complementary tool to experimental and theoretical approaches [6,7]. CFD simulations enable researchers to visualize and analyze complex, unsteady flow patterns around VAWT blades. These insights help optimize airfoil shapes for better performance under different wind conditions. Understanding the intricate relationship between pressure, velocity, and flow behavior is crucial for designing efficient and resilient VAWT blades [8].

Modern small Vertical Axis Wind Turbines (VAWTs) typically operate at low wind speeds, corresponding to low Reynolds numbers, where the flow characteristics differ considerably from those at higher Reynolds numbers. Under these conditions, airfoils are prone to early flow separation and stall, which reduces lift and increases drag, ultimately decreasing the aerodynamic efficiency of lift-based turbines. Due to the low wind speeds and predominantly laminar flow, it is crucial to study airfoil behavior under low Reynolds number conditions. The flow in low Reynolds numbers is unique and has drawn significant research interest. Straight-

bladed VAWTs typically employ symmetric or low-camber airfoils, such as the NACA 0012, which offer limited lift at low Reynolds numbers. Passive flow-control devices can modify the camber and pressure distribution to enhance lift and delay stall. Two such devices are the static extended trailing edge and the Gurney flap.

To meet the demand for high-lift airfoils and self-starting, efficient vertical-axis wind turbines, the aerodynamic features of the airfoils need to be improved. Trailing-edge modifications have long been explored as a means to enhance airfoil performance. The static extended trailing edge (SETE) and Gurney flaps (GFs) are widely regarded as effective devices for enhancing lift, as shown in numerous related studies [9,10,11]. The SETE is a thin, static extension attached to the airfoil's trailing edge, while Gurney flaps are small, flat tabs mounted vertically on the trailing edge of an airfoil, which can effectively improve the airfoil's aerodynamic performance. Among other studies, the initial research on SETEs and GFs for lift enhancement was conducted by Maynard and Evans [12] and by Liebeck [13].

Extended trailing-edge flaps have been extensively studied due to their significant impact on lift generation in aircraft wings. According to Liu *et al.*, [9], extended trailing edge flaps improve an airfoil's lift with minimal drag increase, leading to enhanced airfoil performance [14]. This is achieved by modifying the pressure distribution, transforming the adverse pressure gradient into a plateau, which delays flow separation and enhances lift, especially in the post-stall region [15]. The adverse pressure gradient is the primary cause of flow separation. SETE flaps help delay stall by delaying flow separation, which is critical for improving lift at higher angles of attack [16].

According to Zhao *et al.*, [17], trailing-edge flaps show a nonlinear relationship between driving pressure and the flap's deflection angle. While extending the trailing edge can enhance lift, the effectiveness diminishes with high pressures. This phenomenon is further supported by Jami *et al.*, [18]. Experimental studies by Livya and Pillai [15] show that the SETE can outperform the base airfoil model in lift, especially under high turbulent flow regimes, which further supports its role in delaying flow separation. Boral *et al.*, [19] found that static extended trailing edges reduce the fluctuations in the lift coefficient when analyzing the flow past a circular cylinder with a splitter plate. Adding a trailing edge flap to a static airfoil can significantly improve lift, with increases of over 38% compared to the baseline airfoil [20], particularly at positive angles of attack [21]. Neigapula *et al.*, [22] observed that an extended trailing edge increases the lift coefficient by over 100% at a given angle of attack, enhancing the aerodynamic performance of aircraft wings.

Gurney flaps enhance lift by deflecting the airflow downwards over the lower surface, creating a stronger low-pressure region [11]. Studies on various airfoils have shown that Gurney flaps significantly increase lift coefficients [23,24,25,26]. The height and position of the flap, as well as the angle of attack, influence the generation of lift and drag, with higher Gurney flap heights resulting in increased lift and drag. The presence of Gurney flaps enhances aerodynamic efficiency and

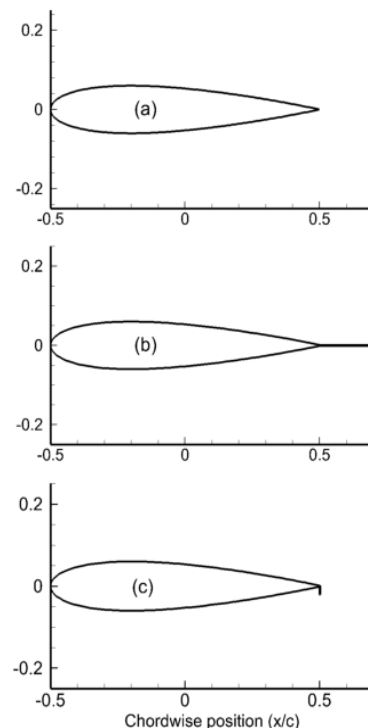
reduces laminar flow separation, mainly in low-pressure turbine blades [26,27].

Most studies in the literature focus on high Reynolds numbers and steady-state behavior. However, real-world conditions often involve unsteady flow environments where periodic shedding, wake dynamics, and temporal variations influence performance. Few papers explore the unsteady behavior of SETE and Gurney flaps together under consistent simulation parameters. This study fills that gap by analyzing both devices on the NACA0012 airfoil under identical flow conditions, therefore offering a comprehensive understanding of their effects in both steady and unsteady flows.

## 2. Numerical Methods

### 2.1. Airfoil Geometry

In this study, the NACA 0012 airfoil, a symmetric profile with a maximum thickness of 12% of the chord, is investigated. Owing to its well-documented aerodynamic characteristics, it serves as a widely accepted benchmark in aerodynamic research. [28]. The SETE flaps were generated by linearly extending the trailing edge of the NACA 0012 airfoil by 10%, 20%, and 30% of the chord length, while maintaining alignment with the original camber line. The Gurney flaps were modeled as small tabs mounted perpendicular to the pressure surface at 99% of the chord, with tested heights of 1%, 2%, and 3% of the chord. Figure 1 shows the baseline NACA 0012 airfoil, the SETE, and the Gurney flap profiles, respectively. All simulations were performed with a normalized chord length of  $c = 1\text{m}$ .



**Figure 1.** (a) Cross-section of the NACA 0012 airfoil, (b) NACA 0012 airfoil with a static extended trailing edge (SETE), and (c) NACA 0012 airfoil with a Gurney flap

## 2.2. Computational Domain

A 2D C-type computational domain was created around the airfoil to accurately capture the flow field and wake effects while minimizing boundary interference. To ensure an adequate computational domain, the upstream boundary extends 10 times the chord length, and the downstream boundary extends 15 times the chord length, as shown in Figure 2, which aligns with the recommendations of Athadkar and Desai [29].

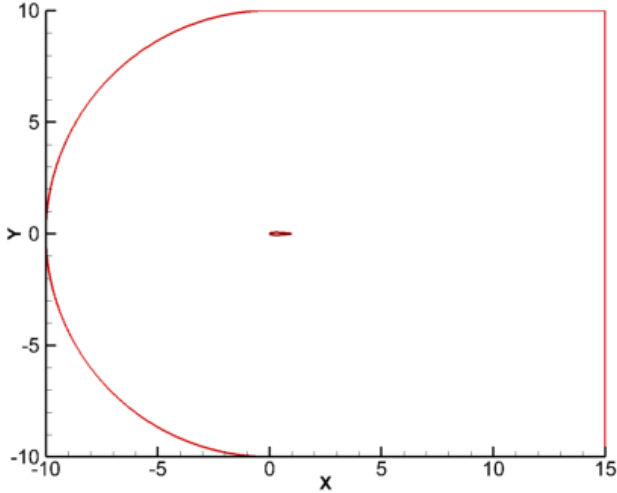


Figure 2. Computational domain

## 2.3. Mesh Generation

A hybrid mesh approach was implemented, using a structured mesh for the outer flow domain and an unstructured mesh near the airfoil to capture flow details more accurately. For both 2D steady and unsteady cases, 20 inflation layers are employed with a growth rate of 1.2, and the first inflation layer thickness starts at 0.27 mm. Additionally, mesh refinement techniques such as edge sizing and adaptive refinement near the leading edge, trailing edge, and wake region were utilized. The following figure illustrates domain discretization and the mesh around the airfoil.

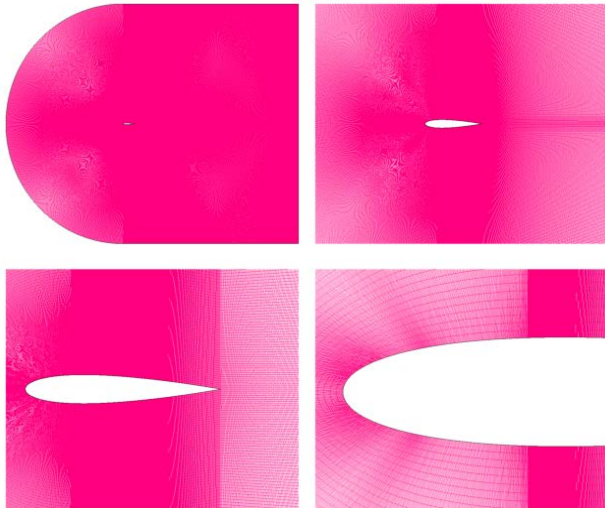


Figure 3. 2D mesh used in simulation

## 2.4. Solver Setup

The Reynolds-Averaged Navier-Stokes (RANS) equations are solved using ANSYS 2024 at a low Reynolds number ( $Re = 2 \times 10^5$ ). The flow is assumed incompressible based on the airfoil chord length, and the angles of attack range from  $-4^\circ$  to  $20^\circ$  in  $2^\circ$  steps. Both steady and unsteady simulations are conducted. For turbulence modeling, the Shear Stress Transport (SST)  $k-\omega$  model is used, as it is particularly effective for providing better accuracy across various flow conditions, including flow separation and adverse pressure gradients [30,31]. The RANS equations are shown below in Equations (1) and (2), followed by the turbulence model equations in Equations (3) and (4).

Continuity Equation:

$$\frac{\partial \bar{u}_i}{\partial x_i} = 0 \quad (1)$$

Momentum Equation:

$$\frac{\partial \bar{u}_i}{\partial t} + \bar{u}_j \frac{\partial \bar{u}_i}{\partial x_j} = -\frac{1}{\rho} \frac{\partial \bar{p}}{\partial x_i} + \frac{\partial}{\partial x_j} \left( (\nu + \nu_t) \left( \frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i} \right) \right) \quad (2)$$

Where:  $\bar{u}_i$  is the time-averaged velocity component in the  $i$ -direction,  $\bar{p}$  is the time-averaged pressure,  $\rho$  is the fluid density,  $\nu$  is the kinematic viscosity, and  $\nu_t$  is the turbulent viscosity (calculated by the SST  $k-\omega$  model).

Turbulent Kinetic Energy ( $k$ ) Equation:

$$\frac{\partial k}{\partial t} + \bar{u}_j \frac{\partial k}{\partial x_j} = P_k - \beta^* \omega k + \frac{\partial}{\partial x_j} \left( (\nu + \sigma_k \nu_t) \frac{\partial k}{\partial x_j} \right) \quad (3)$$

Where:  $k$  is the turbulent kinetic energy,  $\omega$  is the specific dissipation rate, and  $P_k$  is the production of turbulent kinetic energy

Specific Dissipation Rate ( $\omega$ ) Equation

$$\begin{aligned} \frac{\partial \omega}{\partial t} + \bar{u}_j \frac{\partial \omega}{\partial x_j} = & \alpha \frac{\omega}{k} P_k - \beta \omega^2 \\ & + \frac{\partial}{\partial x_j} \left( (\nu + \sigma_\omega \nu_t) \frac{\partial \omega}{\partial x_j} \right) + 2(1 - F_1) \sigma_{\omega 2} \frac{1}{\omega} \frac{\partial k}{\partial x_j} \frac{\partial \omega}{\partial x_j} \end{aligned} \quad (4)$$

Where:  $\alpha, \beta_1, \sigma_\omega$  are model constants,  $F_1$  is the blending function (switches between  $k-\epsilon$  and  $k-\omega$  models), and  $\sigma_{\omega 2}$  is the model constant ( $\sigma_{\omega 2} = 0.856$ ).

The governing equations (continuity, momentum,  $k$ , and  $\omega$ ) are integrated over the control volume for each mesh element. The working fluid is air at  $25^\circ\text{C}$ , and all relevant thermophysical properties are set accordingly. Turbulence modeling uses the SST  $k-\omega$  model, known for its robustness in predicting separation and adverse pressure gradients [30]. Steady-state simulations employ the SIMPLE (Semi-Implicit Method for Pressure-Linked Equations) algorithm for pressure-velocity coupling, while unsteady cases use a second-order implicit scheme for time discretization. All residuals were set to converge below  $1e-6$ . For the steady-state case, the simulation runs until convergence is achieved, monitored by the drag and

lift coefficients. Once these values stabilize, the simulation is considered complete. For the unsteady case, a time step of 0.001 seconds was used, with 50 iterations per time step. The total simulation time varies, typically ranging from 20,000 to 50,000 time-steps, ensuring accurate capture of transient flow behavior.

## 2.5. Inputs and Boundary Conditions

The boundary conditions used in the simulation are summarized in Figure 4. The airfoil surface was defined as a stationary wall with a no-slip condition. The inlet and outlet were specified as a velocity inlet and a pressure outlet, respectively. The flow was assumed to be incompressible, with a constant density of  $1.225 \text{ kg/m}^3$  and dynamic viscosity of  $1.7894 \times 10^{-5} \text{ kg/(m}\cdot\text{s)}$ .

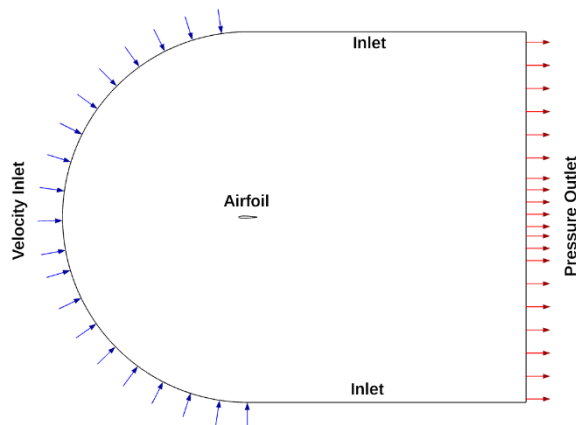


Figure 4. Boundary conditions

## 2.6. Mesh Independency and Validation

Table 1. Mesh Independency Table

| Mesh                       | Element size | Y+  | $C_L$    | $C_D$    | $C_M$    |
|----------------------------|--------------|-----|----------|----------|----------|
| Coarse mesh                | 56406        | 10  | 0.516614 | 0.02712  | -0.12742 |
| Medium mesh                | 324915       | 1   | 0.533573 | 0.012961 | -0.13505 |
| Fine mesh                  | 1270616      | 0.5 | 0.550868 | 0.012384 | -0.13647 |
| Abbott & Von Doenhoff [33] |              |     | 0.55     | 0.012    | -0.132   |

A mesh independence study was performed at  $Re = 6 \times 10^6$  and  $AoA = 5^\circ$  using coarse (56,406 elements), medium (324,915 elements), and fine (1,270,616 elements) meshes. The fine mesh was chosen based on its convergence in  $C_L$ ,  $C_D$ , and  $C_M$ . To establish the credibility of the numerical model, a validation case was performed using a clean NACA0012 airfoil at the same Reynolds number and angle of attack. The results were compared with benchmark data provided by NASA LaRC experimental data [32], which includes data from Abbott and Von Doenhoff [33]. The predicted  $C_L$  and  $C_D$  closely matched the benchmark values within the expected experimental uncertainty, confirming the fidelity of the simulation approach. The simulations employed the SST

$k-\omega$  turbulence model under steady-state conditions. Table 1 presents the mesh variation among the three mesh densities.

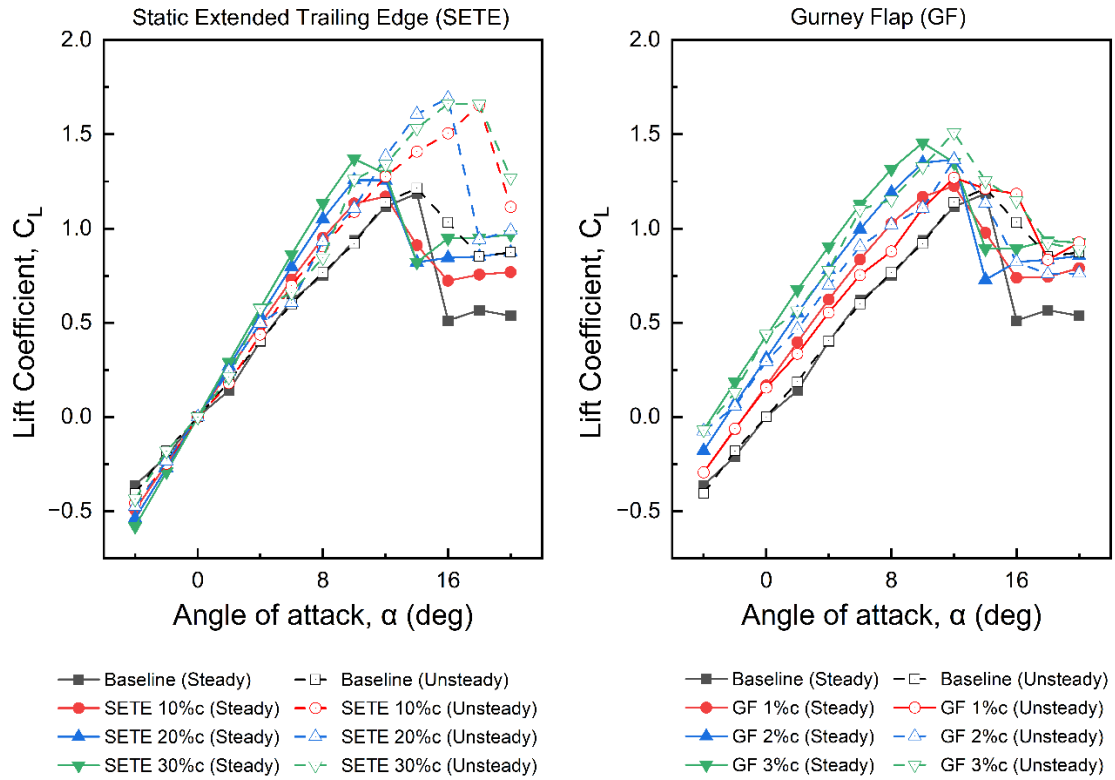
## 3. Results and Discussion

This section compares the aerodynamic performance of the baseline NACA 0012 airfoil with SETE (10%, 20%, 30% chord length) and Gurney flap (1%, 2%, 3% chord length) configurations. Steady and unsteady results are discussed in parallel, focusing on lift ( $C_L$ ), drag ( $C_D$ ), lift-to-drag ratio ( $L/D$ ), moment coefficient ( $C_M$ ), and pressure coefficient ( $C_p$ ). The findings highlight both the benefits and trade-offs of these trailing-edge devices.

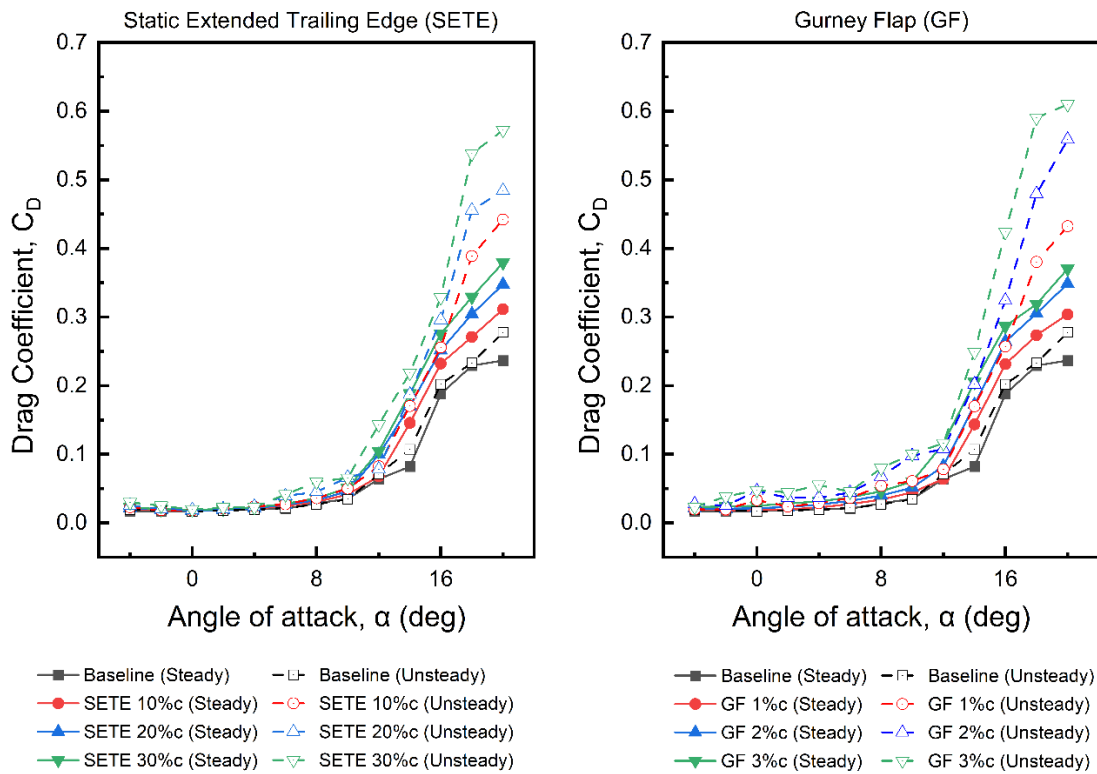
### 3.1. Lift and Drag Coefficients

The lift characteristics of the baseline and modified NACA0012 airfoils, under both steady and unsteady flow conditions, are shown in Figure 5. The baseline showed a nearly linear increase in lift coefficient ( $C_L$ ) with angle of attack up to  $14^\circ$ , after which stall occurred, accompanied by either a reduction in lift or a plateau. In this study, the steady-flow maximum was  $C_{L,max} = 1.116$  at  $AoA = 14^\circ$ , while under unsteady flow conditions, the peak increased to  $C_{L,max} = 1.214$  at the same angle of attack. This behavior strongly agrees with Ladson's static measurements [34] and the dynamic-stall investigations by McAlister [35] and Tsang *et al.*, [36], all of whom reported comparable load excursions and vortex-induced lift amplification for NACA0012 under unsteady flow. All three SETE configurations showed progressive lift improvements compared to the baseline NACA0012 airfoil. Under steady flow, SETE 10%c, SETE 20%c, and SETE 30%c achieved  $C_{L,max}$  values of 1.170 (+4.8%), 1.257 (+12.7%), and 1.370 (+22.8%), respectively, indicating better pressure recovery and delayed flow separation at moderate angles of attack. Under unsteady conditions, this trend continued, with SETE 20%c reaching  $C_{L,max} = 1.690$  at  $16^\circ$  (+39.2% versus baseline peak at  $14^\circ$ ), while SETE 30%c further increased the post-stall lift plateau to 1.65. These findings align with Liu *et al.*, [9], who demonstrated that thin trailing-edge extensions on NACA0012 effectively shift the lift curve upward, reduce abrupt stall onset, and incur only modest drag penalties. The current data also indicate that SETE devices benefit disproportionately from unsteady effects, with post-stall lift decaying more gradually than for the baseline airfoil.

Gurney flaps produced more immediate and pronounced lift increases across the entire  $AoA$  range. Under steady flow, GF 1%c reached  $C_{L,max} = 1.227$  (+5.2%), GF 2%c = 1.366 (+17.1%), and GF 3%c = 1.456 (+24.8%). In unsteady flow, peak values occurred earlier and higher than the baseline's dynamic-stall maximum, with GF 1%c at



**Figure 5.** Lift coefficient ( $C_L$ ) versus angle of attack ( $\alpha$ ) for Baseline airfoil, Static Extended Trailing Edges (SETE), and Gurney Flaps (GF) under steady and unsteady flow



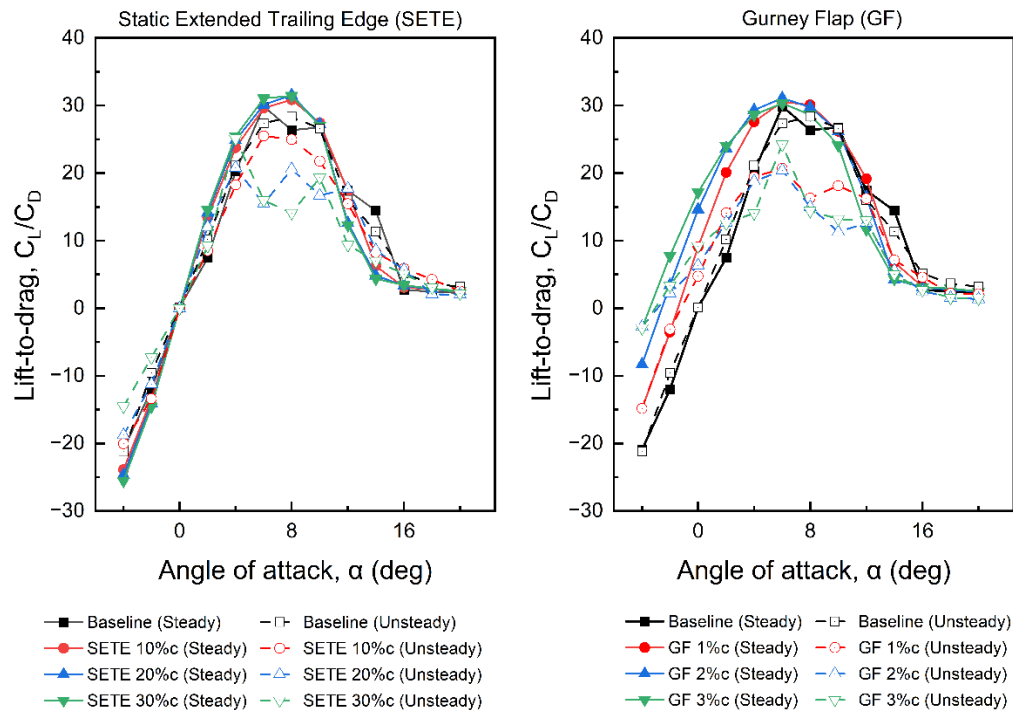
**Figure 6.** Drag coefficient ( $C_D$ ) versus angle of attack ( $\alpha$ ) for Baseline airfoil, Static Extended Trailing Edges (SETE), and Gurney Flaps (GF) under steady and unsteady flow

1.269 (+4.5%), GF 2%*c* at 1.363 (+12.3%), and GF 3%*c* at 1.509 (+24.3%), yet still delivered significantly higher pre-stall lift. These lift-drag trade-offs closely match the results of Jang *et al.*, [37], Li *et al.*, [38], Jain *et al.*, [27], and Aminiet *al.*, [39], who reported lift enhancements of 15-40%, along with increased drag and intensified trailing-edge vortex formation when applying Gurney flaps to symmetric profiles. Notably, this study confirms that unsteady flow increases the peak  $C_L$  by about 0.1-0.2 units for both SETE and GF configurations, while also reducing the post-stall decline.

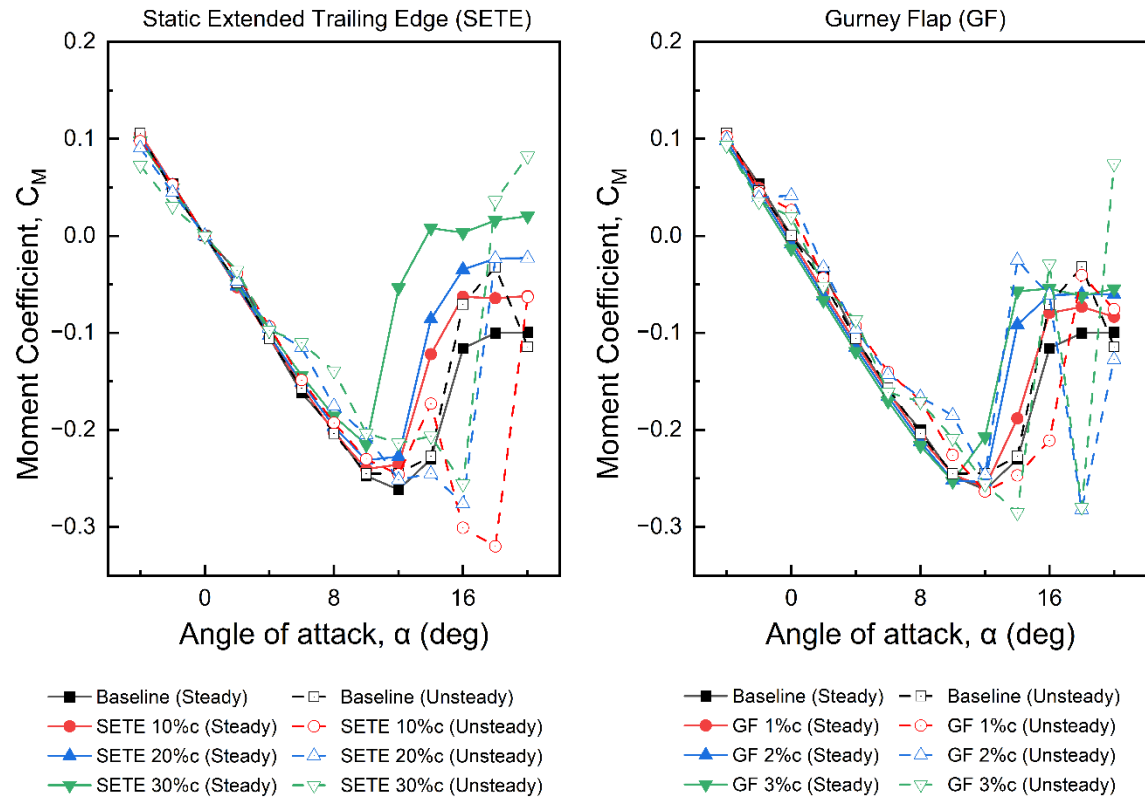
Figure 6 displays the drag coefficient versus the angles of attack for SETEs and GFs under both steady and unsteady flow conditions. Under steady flow, at the angles of attack corresponding to each airfoil configuration's  $C_{L,max}$ , the baseline airfoil's drag coefficient was 0.082. Adding Static Extended Trailing Edge reduced the drag to 0.068 (-17.5%), 0.046 (-43.8%), and 0.051 (-38.3%) for SETE 10%*c*, 20%*c*, and 30%*c*, respectively, compared to the baseline. Gurney flaps showed a similar trend, with GF 1%*c* at 0.064 (-22.2%), GF 2%*c* at 0.083 (+0.8%), and GF 3%*c* at 0.06 (-26.6%). In unsteady flow, the baseline's drag at peak lift increased slightly to 0.087, while the SETEs and GFs reached their peaks at lower angles of attack, with drag coefficients at their respective  $C_{L,max}$ , significantly different from the steady-state values. For example, SETE 20%*c* at 0.176 (+101.6%) and GF 2%*c* at 0.108 (+23.7%). This contrast between steady and unsteady conditions was also noted by Liu *et al.*, [9], and Jang *et al.*, [37], who observed that trailing-edge devices shift performance toward higher lift at the cost of increased drag under steady flow; however, during dynamic stall, the altered flow development causes earlier peaks and different drag behavior at  $C_{L,max}$ .

### 3.2. Lift-to-drag Ratio

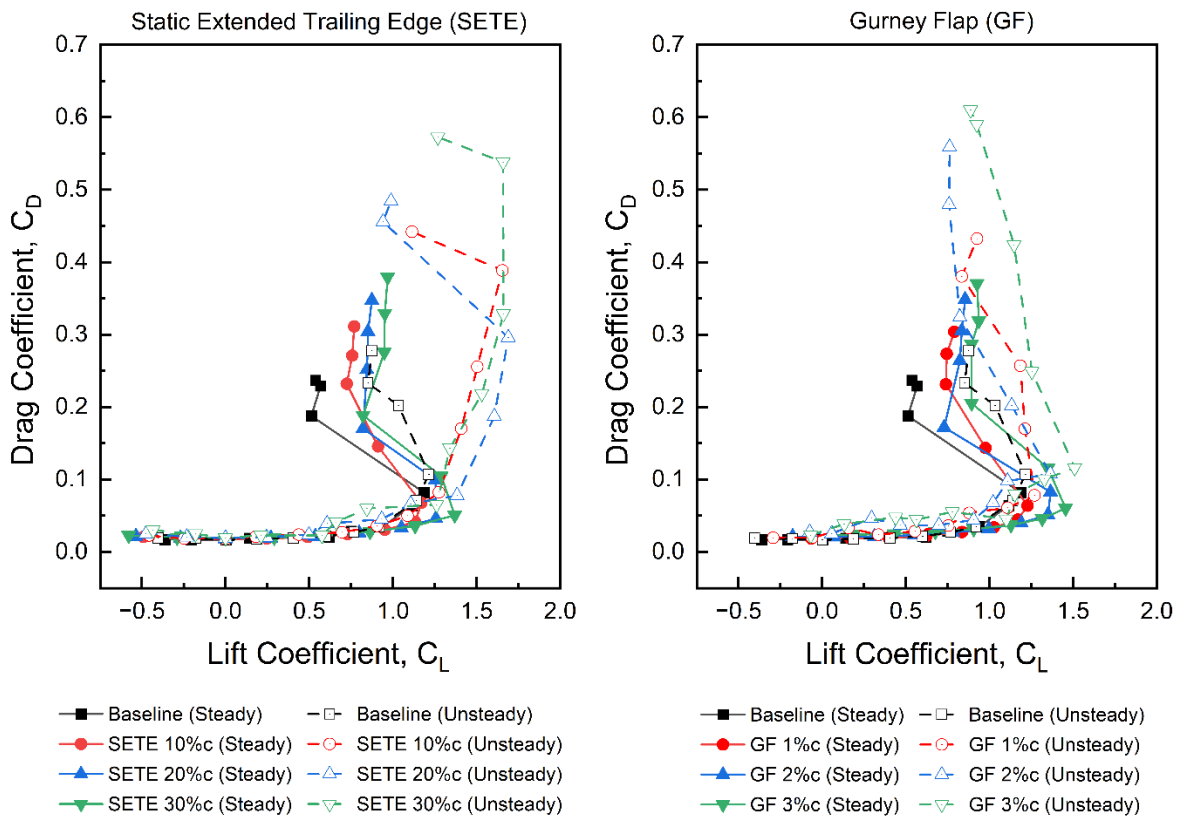
Figure 7 shows the variation in lift-to-drag ratio (CL/CD) with angle of attack for the baseline and modified configurations. The baseline NACA0012 profile showed the expected behavior, with aerodynamic efficiency steadily increasing with the angle of attack, peaking at  $\text{AoA} = 6^\circ$ , then dropping sharply. Under steady conditions, the baseline reached a maximum L/D of 29.9 at  $\text{AoA} = 6^\circ$ , while under unsteady conditions, the peak shifted to  $L/D = 28.3$  at  $\text{AoA} = 8^\circ$ . This pattern matches typical data for NACA0012 [34,36], which typically exhibits peak efficiency at moderate angles before experiencing a rapid stall. The SETE extensions improved aerodynamic efficiency over a wide AoA range under steady flow. SETE 20%*c* achieved the highest L/D of 31.5 (+5.6% compared to baseline), followed closely by SETE 30%*c* at 31.4 (+5.2%). These improvements are likely due to delayed stall onset, smoother pressure recovery, and reduced wake losses, mechanisms previously discussed by Liu *et al.*, [4]. However, under unsteady flow, the efficiency benefits decreased: SETE 20%*c* dropped to  $L/D = 20.8$  (-26.6% compared to baseline peak), even though it maintained higher lift beyond  $\text{AoA} = 10^\circ$ . Under steady conditions, moderate Gurney flaps also increased peak efficiency; GF 2%*c* achieved  $L/D = 31.1$  (+4.1%) at its optimal angle. But all flap heights experienced rapid efficiency drops beyond  $\text{AoA} = 6^\circ$ , and under unsteady flow, the decline was more noticeable and irregular. For example, GF 2%*c* fell to  $L/D = 20.4$  (-28.1% compared to baseline) at its dynamic-stall peak. These results support the findings of Li *et al.*, [38] and Jain *et al.*, [27], who observed that Gurney flaps improve lift before but cause higher drag and stronger vortex shedding under unsteady inflow



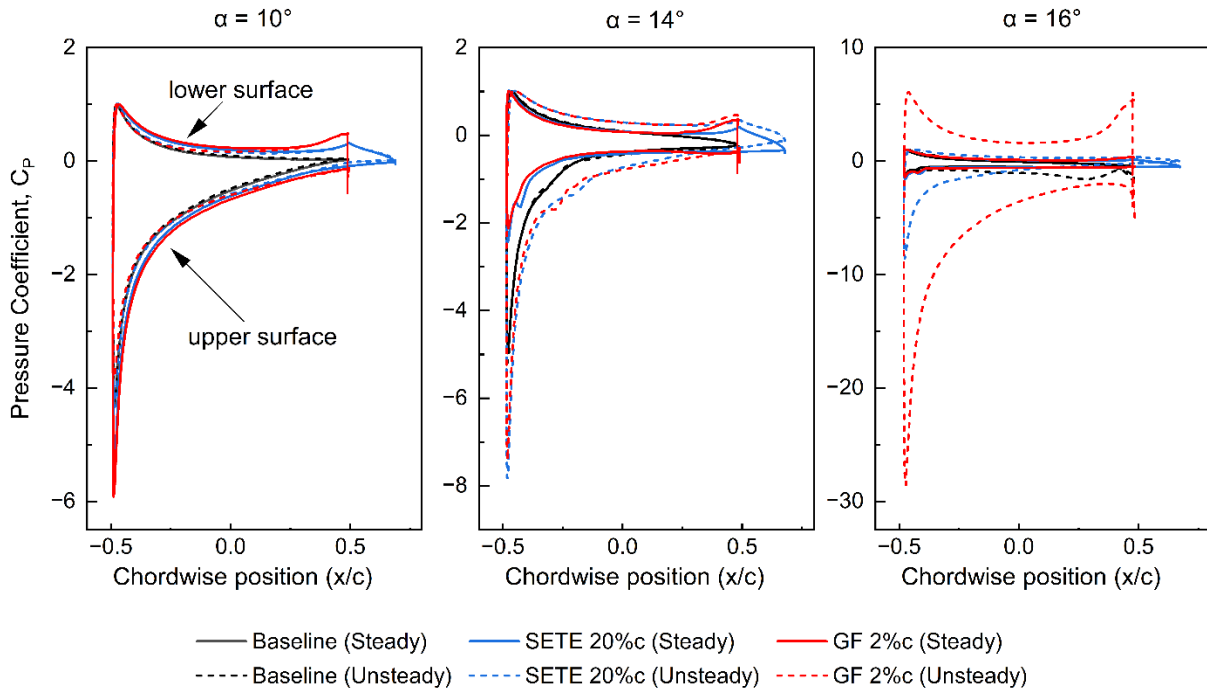
**Figure 7.** Lift-to-drag ratio ( $C_L/C_D$ ) versus angle of attack ( $\alpha$ ) for Baseline airfoil, Static Extended Trailing Edges (SETE), and Gurney Flaps (GF) under steady and unsteady flow



**Figure 8.** Moment coefficient ( $C_M$ ) versus angle of attack ( $\alpha$ ) for Baseline airfoil, Static Extended Trailing Edges (SETE), and Gurney Flaps (GF) under steady and unsteady flow



**Figure 9.** Polar curves ( $C_L$ - $C_D$ ) for the Baseline airfoil, Static Extended Trailing Edges (SETE), and Gurney Flaps (GF), showing the shift in lift and drag characteristics across various angles of attack, highlighting lift augmentation and drag penalties relative to the baseline



Note: The y-axis scales differ among plots.

**Figure 10.** Pressure coefficient distributions ( $C_p$ ) at angles of attack,  $\alpha = 10^\circ$ ,  $14^\circ$ , and  $16^\circ$  for the baseline, SETE 20%c, and GF 2%c under steady and unsteady flow

### 3.3. Moment Coefficient

The pitching moment behavior of the baseline NACA 0012 airfoil, SETEs, and GFs is illustrated in Figure 8. The baseline airfoil followed the expected trend of a gradual decrease in  $C_M$  as the angle of attack (AoA) increased, indicating the forward shift of the aerodynamic center and the resulting nose-down pitching moment. With the addition of Static Extended Trailing Edges (SETE), this nose-down tendency becomes noticeable, especially at moderate to high AoA, as increased lift and a rearward shift of the center of pressure strengthen the negative  $C_M$  values. These observations match published results for symmetric airfoils [34]. SETEs kept smooth and predictable  $C_M$  curves under steady and unsteady conditions. Gurney flaps also increased the magnitude of negative  $C_M$ , with the effect growing as flap height increases; the GF 3%c shows the most noticeable nose-down moment. However, unsteady results reveal unpredictable behavior beyond  $10^\circ$  AoA. While both trailing edge modifications increased the nose-down moment, SETE provided a more stable and predictable response, whereas Gurney flaps caused greater unsteadiness at high AoA. From  $10^\circ$  AoA onward, the unsteady moment coefficient curves showed non-linear and unpredictable trends, compared to the steady-state results, which varied more smoothly. This behavior likely results from the start of dynamic stall, where vortex formation and shedding significantly change the pressure distribution over the airfoil. Additionally, the unsteady interaction between the flap-induced wake and the oscillating boundary layer can enhance these effects, leading to the observed irregularities.

### 3.4. Overall Performance and Optimal Balance

When evaluating lift, drag, efficiency, and moment characteristics together, SETE 20%c and GF 2%c consistently stand out as the most balanced airfoil modifications. The SETE 20%c offers high lift, controlled drag increase, competitive efficiency, and stable pitching behavior, while GF 2%c provides similar benefits among Gurney flaps, delivering significant lift enhancement and efficiency without the severe penalties seen in GF 3%c. Therefore, although SETE 30%c and GF 3%c represent maximum lift designs, SETE 20%c and GF 2%c emerge as the optimal choices, providing the overall balance across all aerodynamic parameters. To understand the flow mechanisms behind the aerodynamic performance of the baseline airfoil and the two top performers, SETE 20%c and GF 2%c, the surface pressure distributions and unsteady vorticity fields were analyzed at AoA =  $10^\circ$ ,  $14^\circ$ , and  $16^\circ$  as shown below.

### 3.5. Pressure Distribution

Figure 10 displays the pressure coefficient distribution over the baseline, SETE 20%c, and GF 2%c at AoA of  $10^\circ$ ,  $14^\circ$ , and  $16^\circ$ , respectively. Negative  $C_p$  values indicate suction. The SETE and Gurney flaps shift the suction peak and influence the pressure recovery region near the trailing edge, affecting lift generation and stall delay. At AoA =  $10^\circ$ , the baseline airfoil shows a typical suction peak near the leading edge, accompanied by

smooth pressure recovery. The SETE 20%c causes a slight aftward shift in the suction peak while improving the pressure gradient near the trailing edge, leading to increased lift. The GF 2%c produces a steeper suction peak, indicating a higher lift coefficient at this angle. However, at  $\text{AoA} = 14^\circ$ , both SETE and GF show a flattened  $C_p$  profile near the trailing edge, confirming early separation and reduced control over the adverse pressure gradient, especially for GF 2%c. SETE 20%c, on the other hand, maintains a more favorable gradient, resulting in better flow attachment and delayed stall onset. The  $C_p$  plots show stronger suction peaks for GFs but more gradual and stable pressure recovery for SETE devices. Vorticity contours confirmed early separation and intense vortex shedding for GF 20%c beyond  $14^\circ$ , while SETE 20%c maintained attached flow and organized wakes even at  $16^\circ$  AoA. These effects align with those of Liu *et al.*, [40] and Ethiraj and Pillai [41], who demonstrated that trailing edge modifications enhance lift through pressure recovery, while Gurney flaps act through vortex augmentation.

### 3.6. Vorticity Contours

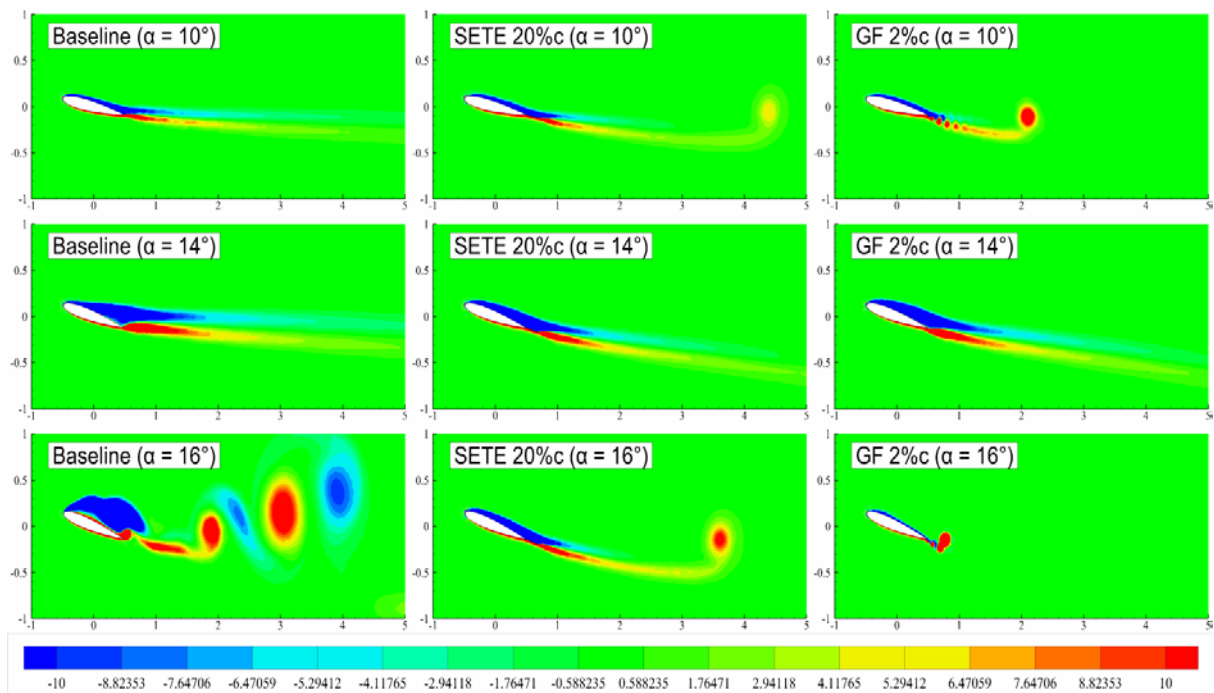
Figure 11 displays the vorticity contours at  $\text{AoA} = 10^\circ$ ,  $14^\circ$ , and  $16^\circ$  for the baseline, SETE 20%c, and GF 2%c under unsteady flow. At  $10^\circ$  AoA, the baseline already shows the start of weak shear-layer vortices, while the SETE 20% and GF 2%c setups exhibit delayed vortex formation and smaller wake thickness. At  $14^\circ$  and  $16^\circ$  AoA, the baseline airfoil produces large, disorganized vortical structures, indicating unsteady separation and lift breakdown. The SETE setup effectively suppresses some of this chaotic vorticity, promoting a more stable flow in both steady and unsteady conditions. The Gurney flap displays intense, periodic vortex shedding, consistent with

its known behavior of energizing the wake but potentially increasing oscillatory forces.

## 4. Conclusion

This study evaluated the aerodynamic performance of the NACA 0012 airfoil with trailing-edge modifications under steady and unsteady flow conditions at a Reynolds number of  $2 \times 10^5$ . Seven configurations were examined: the baseline, three Static Extended Trailing Edges (SETEs of 10%, 20%, and 30% chord length), and three Gurney flaps (GFs of 1%, 2%, and 3% chord height). Numerical simulations utilized both Reynolds-Averaged Navier–Stokes (RANS) and Unsteady RANS (URANS) formulations, with validation against NASA benchmark data at  $\text{Re} = 6 \times 10^6$  and  $\text{AoA} = 5^\circ$ .

The baseline NACA 0012 served as the control case, showing typical lift behavior of a symmetric airfoil. There were distinct aerodynamic mechanisms involving static extended trailing edges and Gurney flaps. Gurney flaps maximize lift across the AoA spectrum and maintain post-stall lift. However, their steep drag penalties, unstable L/D performance, and erratic pitching moments limit their use in efficiency-driven systems. The SETEs, on the other hand, offer smoother and more balanced aerodynamic improvements. Among the tested cases, the SETE20%c and GF2%c consistently stand out as the most balanced designs, providing significant lift gains while maintaining efficiency levels similar to the baseline. The 20%c SETE delivered the best combination of high lift, low drag, delayed stall, and stable moment behavior. These characteristics make the SETE 20%c extension very promising for small-scale vertical-axis wind turbines (VAWTs).



**Figure 11.** Vorticity contours at  $\alpha = 10^\circ$ ,  $14^\circ$ , and  $16^\circ$  for the baseline, SETE 20%c, and GF 2%c under unsteady flow

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