

Parametric Airfoil Cross-Section Effects on Grid Fin Aerodynamic Performance

Yoyi L. Xie,^{*} Edward Y. Huang,^{*} Jack R. Rumpf,^{*} Kaylin Wu,[†] and Szu Heng Chen[†]

Grid fins are unconventional aerodynamic control surfaces composed of an intersecting lattice of struts enclosed within a rigid frame. Compared to traditional planar fins, grid fins provide increased effective control surface area per unit projected area, enabling strong aerodynamic authority at the cost of increased parasitic drag and reduced efficiency. These characteristics have led to their widespread use in modern launch vehicles and guided systems, particularly for atmospheric reentry and precision guidance. Grid fin performance is strongly influenced by geometric parameters such as lattice spacing, strut thickness, and cross-sectional shape, which has historically been limited by manufacturing constraints. This study investigates the aerodynamic impact of redesigning grid fin strut geometry by replacing conventional rectangular struts with airfoil cross-sectional strut designs enabled by additive manufacturing. Two-dimensional Reynolds-averaged Navier–Stokes simulations (RANS) were performed using the SST $k-\omega$ turbulence model on stacked airfoil configurations. Individual airfoil profiles were modified with 4 parametric variations in leading-edge radius and thickness distribution, with NACA 0012 and rectangular geometries as a control. This study was performed with up to 45 degrees angles of attack (AoA) and freestream velocities from 0.1 to 0.3 Mach. Increasing AoA introduced nonlinear aerodynamic behavior across the stacked configurations, with interelement interference notably influencing separation behavior. Velocity sweeps revealed pronounced Reynolds number dependent behavior, with several geometries showing changes in separation characteristics and force response as velocity increased. These trends demonstrate tradeoffs between aerodynamic response and operational envelope, highlighting the sensitivity of grid fin aerodynamic behavior to cross-sectional geometry.

I. Nomenclature

AoA	=	Angle of Attack
LE	=	Leading Edge
TE	=	Trailing Edge
t_{max}	=	Location of Max Thickness
C_L	=	Coefficient of Lift
C_D	=	Coefficient of Drag
C_M	=	Coefficient of Moment

II. Introduction

GRID fins are lattice-based aerodynamic control surfaces composed of intersecting struts enclosed within a rigid frame. Their enclosed lattice provides high control authority for a given projected planform area and supports compact packaging, which is advantageous for guidance and descent control applications [1, 2]. Grid fins have been implemented on operational flight vehicles, notably the SpaceX *Falcon 9* and *Falcon Heavy* launch vehicles for atmospheric guidance and booster recovery, and similar concepts have long been used on missile systems and other launch vehicles across a broad range of flight conditions [2, 3]. The primary drawback of grid fins is aerodynamic efficiency: the internal passages promote flow blockage, separation, and wake interaction, producing substantial parasitic drag and strong nonlinearity as incidence increases [1].

^{*}Undergraduate Student, Woodruff School of Mechanical Engineering, Atlanta, GA, 30332, AIAA University Student.

[†]Undergraduate Student, Guggenheim School of Aerospace Engineering, Atlanta, GA, 30332, AIAA University Student.

Extensive prior research has therefore characterized how grid-fin performance varies with fin scale, lattice proportions, and flow regime. Representative free-flight and wind-tunnel datasets for subscale missile geometries commonly examine grid fins with span on the order of one caliber and comparatively small chord; in one configuration, the grid-fin span is 1.1 cal and the chord is 0.17 cal, with measurements spanning subsonic through transonic conditions (e.g., $M \approx 0.39$ – 1.65) where compressibility and internal-cell wave structure begin to dominate drag trends [4]. Complementary parametric studies isolate inner-lattice geometry using dimensionless ratios, sweeping quantities such as width-to-chord and thickness-to-width under subsonic conditions [5]. Across these investigations, increasing lattice depth and/or blockage proxies tends to increase normal-force capability and control authority, but at the cost of higher pressure drag due to strengthened blockage, internal separation, and wake interaction. These penalties generally intensify toward transonic conditions as shock formation, choking tendencies within cells, and wave–boundary-layer interaction become more influential [4, 5].

To mitigate drag penalties, multiple geometry-level strategies have been studied using targeted parameter sweeps. Cai investigated compressibility-driven choking behavior over grid-fin configurations and showed that aerodynamic coefficients increase with both freestream Mach number and angle of attack (AOA), highlighting how confined passages can trigger rapid drag growth once blockage effects become significant [6]. Washington *et al.* examined curvature and leading-edge sweepback effects, demonstrating that outer-frame shaping and sweepback provide viable degrees of freedom for managing high-speed drag mechanisms while preserving primary control-force trends [7]. More recently, Li *et al.* quantified lattice-topology sensitivity by varying internal cell layout (e.g., reducing cell count from a 6×6 baseline through a 2×2) and evaluating performance across discrete Mach and incidence schedules [8]. These studies indicate that drag mitigation approaches involve both external-frame shaping and internal topology modification, with benefits varying according to the Mach–AoA envelope instead of exhibiting uniform effectiveness across regimes.

Despite these developments, relatively few investigations treat the cross-sectional shape of individual lattice members as a primary aerodynamic design parameter in subsonic regimes. Rectangular member cross-sections are frequently assumed in practice because conventional machining imposes tool-access and fixturing constraints within a closed lattice, making continuous internal airfoil-shaped members impractical to fabricate without segmentation and assembly. Yet, member profile directly governs local separation and wake development inside the lattice, and thus influences form drag, blockage, and wake-interaction losses; prior cascade and lattice-flow studies indicate that airfoil-shaped members can reduce form drag and delay separation relative to rectangular profiles [9]. Recent advances in additive manufacturing mitigate these internal-access limitations and enable precise shaping of enclosed members without prohibitive cost, motivating the present study to quantify how airfoil cross-section lattice members alter stacked grid-fin aerodynamic performance in subsonic flow [10].

III. Methodology

A. Geometry and Flow Conditions

A two-dimensional (2D) representation of a grid-fin cross-section was modeled as a stacked, multi-element “ladder” configuration consisting of four identical strut sections arranged normal to the freestream direction. Each member had chord length $c = 0.1$ m and was positioned with a center-to-center gap of $g = 0.05$ m ($g/c = 0.5$). A gap-to-chord ratio of $g/c = 0.5$ was chosen as an intermediate spacing that preserves measurable cascading (interference) effects while avoiding the stronger lift suppression at smaller g/c and limiting the drag increase and reduced stall angle observed at larger g/c [9]. All members were aligned in the streamwise direction with coincident leading and trailing edges. The stack was centered about the global midline ($y = 0$), and members were equally spaced.

The baseline strut geometry used a symmetric NACA 0012 profile, selected as a standard reference baseline with a fixed, well-defined section that enables parameterizable control of geometry across cases. A rectangular strut with equivalent cross-sectional area and chord length to the NACA 0012 profile was used as an additional comparison geometry; the rectangle thickness was $t = 8.447$ mm with sharp leading and trailing edges. Airfoil variants were generated parametrically via the mathematically defined curve:

$$y_t(x) = t \left[a_0 \sqrt{\frac{x}{c}} + a_1 \left(\frac{x}{c} \right) + a_2 \left(\frac{x}{c} \right)^2 + a_3 \left(\frac{x}{c} \right)^3 + a_4 \left(\frac{x}{c} \right)^4 \right], \quad 0 \leq x \leq c$$

Two classes of geometric modifications were examined: (i) leading-edge (LE) radius adjustment by applying multiplicative scaling to the analytic NACA nose-radius formulation ($0.5\times$ and $2\times$ the baseline value), and (ii) shifting

the location of maximum thickness to $x_t/c = 0.25$ and 0.35 relative to a baseline $x_t/c = 0.30$ while preserving maximum thickness magnitude ($t/c = 0.12$). Individual geometries are shown in Fig. 1, with assembly-level views in Fig. 2.

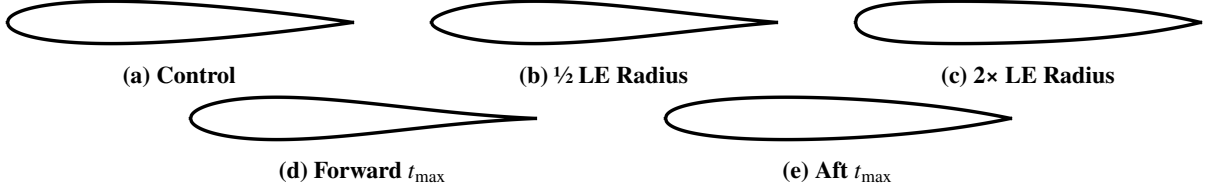


Fig. 1 Airfoil geometries investigated.

Freestream conditions corresponded to sea-level air at room temperature, modeled as a compressible ideal gas with temperature-dependent viscosity using Sutherland's law. The freestream static temperature and pressure were set to $T_\infty = 288.15$ K and $p_\infty = 101325$ Pa, respectively. Simulations were performed over freestream Mach numbers $M_\infty = 0.1$ – 0.3 and angles of attack α from 0° to 45° in discrete 5° increments. Angle of attack was implemented by prescribing inlet velocity components corresponding to the desired M_∞ and α while keeping the geometry fixed. A turbulence intensity of 0.5% and length scale $l = 0.01$ m were imposed at the inlet boundary. A compressible framework was chosen to better capture pressure-wave interactions in confined inter-element gaps, and for consistency in comparisons with anticipated studies in higher Mach number regimes.

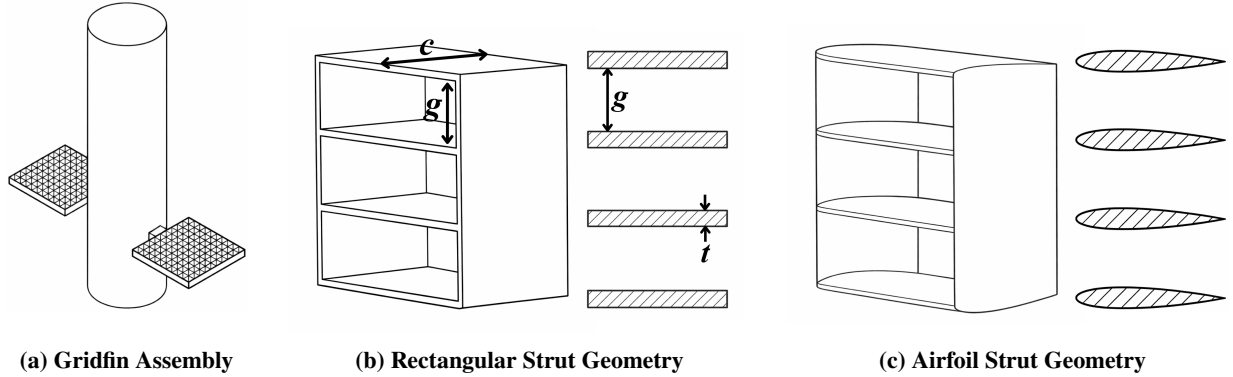


Fig. 2 Lattice geometries

B. Mesh and Boundary Conditions

The computational domain used a 2D C-grid topology to reduce blockage and provide controlled resolution upstream and in the wake. The velocity inlet boundary on the upstream C-arc was located $30c$ upstream of the leading edge, and the outlet plane was located $50c$ downstream of the leading edge. The outer farfield boundary had a characteristic radius of 3 m, which places the farfield approximately $30c$ from the geometry.

The upstream C-arc boundary was specified as a velocity inlet with components set to enforce the desired M_∞ and α , with $T_\infty = 288.15$ K. The downstream boundary was specified as a pressure outlet with zero gauge pressure; backflow temperature was set to 288.15 K and backflow turbulence quantities matched the inlet specification. The outer boundary was treated as a pressure far-field boundary, with freestream specification consistent with inlet. All strut surfaces were modeled as smooth, no-slip, adiabatic walls with the energy equation enabled. Integrated wall treatment was used with near-wall resolution targeted to $y^+ < 1$ so the viscous sublayer is resolved and wall shear is computed directly, reducing reliance on wall-function assumptions and improving accuracy in nonequilibrium regions such as adverse pressure gradients and separation.

The mesh, shown in Fig. 3 consisted of an unstructured triangular grid with local refinement concentrated around the strut surfaces and in the inter-element gap regions to resolve shear layers and separation. Boundary-layer inflation was applied on all strut surfaces using 20 layers, a growth rate of 1.15 , and a first-layer height of $\Delta y_1 = 2 \times 10^{-6}$ m, selected to maintain $y^+ < 1$ across the operating envelope, calculated as $y^+ = \frac{u_\tau y}{\nu} = \frac{\rho u_\tau y}{\mu}$, $u_\tau = \sqrt{\frac{\tau_w}{\rho}}$. The typical

global cell count per case was approximately 1.5×10^5 cells with additional body-fitted refinement in the near-field. The present study uses a consistent meshing strategy across all geometries and flow conditions to support comparative evaluation of profile-driven trends.

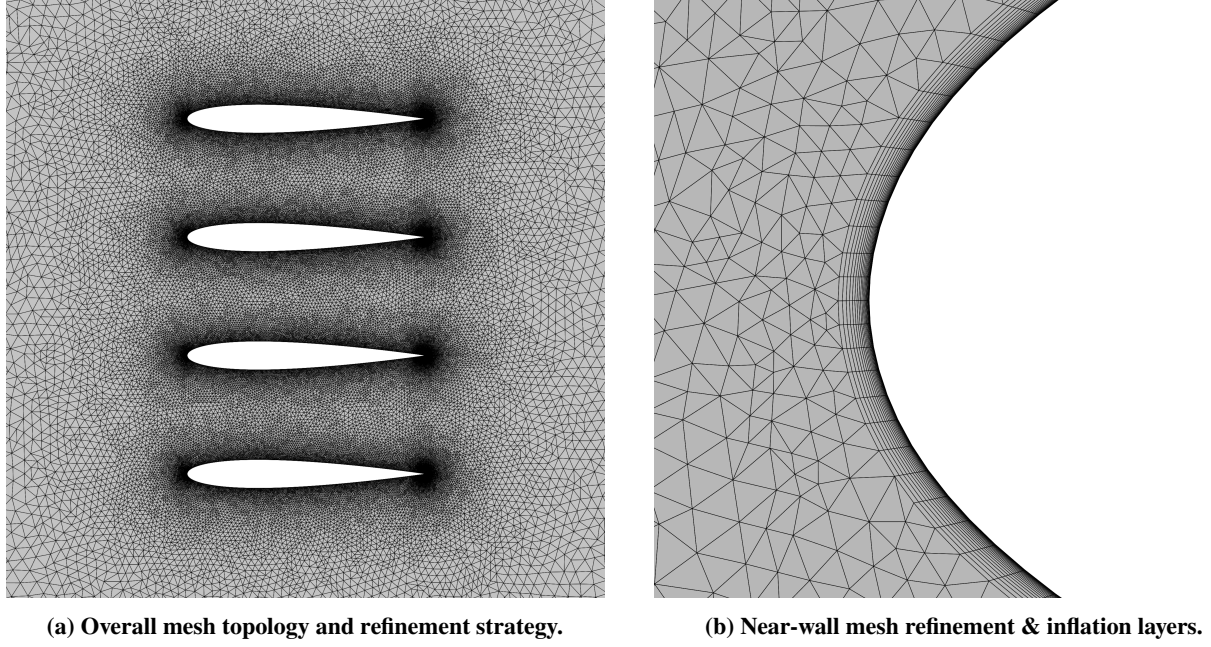


Fig. 3 Computational mesh for NACA0012 airfoil stack.

C. Governing Equations

Flow solutions were obtained in ANSYS Fluent using a pressure-based, double-precision compressible approach. The governing equations were the compressible Reynolds-averaged Navier–Stokes (RANS) equations expressed for conservation of mass, momentum, and total energy, coupled with a turbulence closure. In conservative form:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0, \quad (1)$$

$$\frac{\partial (\rho \mathbf{u})}{\partial t} + \nabla \cdot (\rho \mathbf{u} \mathbf{u}) = -\nabla p + \nabla \cdot \left[(\mu + \mu_t) \left(\nabla \mathbf{u} + (\nabla \mathbf{u})^T - \frac{2}{3} (\nabla \cdot \mathbf{u}) \mathbf{I} \right) \right], \quad (2)$$

$$\frac{\partial (\rho E)}{\partial t} + \nabla \cdot (\mathbf{u} (\rho E + p)) = \nabla \cdot [(k + k_t) \nabla T] + \Phi, \quad (3)$$

where ρ is density, $\mathbf{u}$ is velocity, p is static pressure, E is total energy per unit mass, μ is molecular viscosity (Sutherland’s law), μ_t is eddy viscosity, k is thermal conductivity, k_t is turbulent thermal conductivity, and Φ represents viscous dissipation terms.

Turbulence closure was provided by the Menter shear-stress transport (SST) k – ω model, and transition effects were modeled using the γ – Re_θ transition SST approach with default model constants. Unsteady RANS (URANS) simulations were performed to capture unsteady separation and interference effects between members at elevated angles of attack. Pressure–velocity coupling used the SIMPLEC algorithm. Spatial discretization employed second-order accurate schemes for all transported variables with second-order implicit time integration and second-order upwind treatment for convective fluxes.

A constant time step of $\Delta t = 2 \times 10^{-5}$ s was used as a computationally feasible choice for the parametric sweep, with 20 inner iterations per time step. All simulations were advanced to $t = 1$ s, equivalent to approximately 4.25 through-domain convective times, $\tau_c = L/U_{\text{ref}}$. The reference velocity was based on the $M_\infty = 0.3$ freestream condition. Aerodynamic forces and moments were monitored for stabilization; reported coefficients correspond to time-averaged values computed over the final 0.2 s of the transient response after the solution reached a statistically stationary regime.

Aerodynamic coefficients were computed using freestream density and velocity, with reference length $L_{\text{ref}} = c$ and reference area $S_{\text{ref}} = c \times 1$ (unit span). Lift and drag were resolved in a coordinate system aligned with the freestream direction. Integrated C_L , C_D , and pitching moment coefficient C_M were computed for the full four-member stack, and per-member coefficients were also extracted. Moments were referenced about the geometric center of the chord line at $(x_{\text{ref}}, y_{\text{ref}}) = (0.05, 0)$ m with positive C_M defined as nose-up.

IV. Results and Discussion

This section presents the results for the stacked-member cross-sections (rectangular, NACA 0012, two leading-edge (LE) radius variants, and two maximum thickness location variants) across the simulated freestream Mach number M_∞ and angle of attack (AoA) α sweeps. Reported coefficients are time-averaged over the final 0.2 s of each unsteady Reynolds-averaged Navier–Stokes (URANS) simulation and correspond to the integrated four-member stack. Within each plot, curves for $M_\infty = 0.1, 0.2$, and 0.3 are overlaid to show velocity (Reynolds number (Re)) dependence directly.

A. Baseline Comparison: Rectangular Versus NACA 0012

This subsection compares the conventional rectangular strut cross-section to the symmetric NACA 0012 baseline while holding stacked spacing and chord fixed. Fig. 4 summarizes the effects on lift, drag, aerodynamic efficiency, and pitching moment.

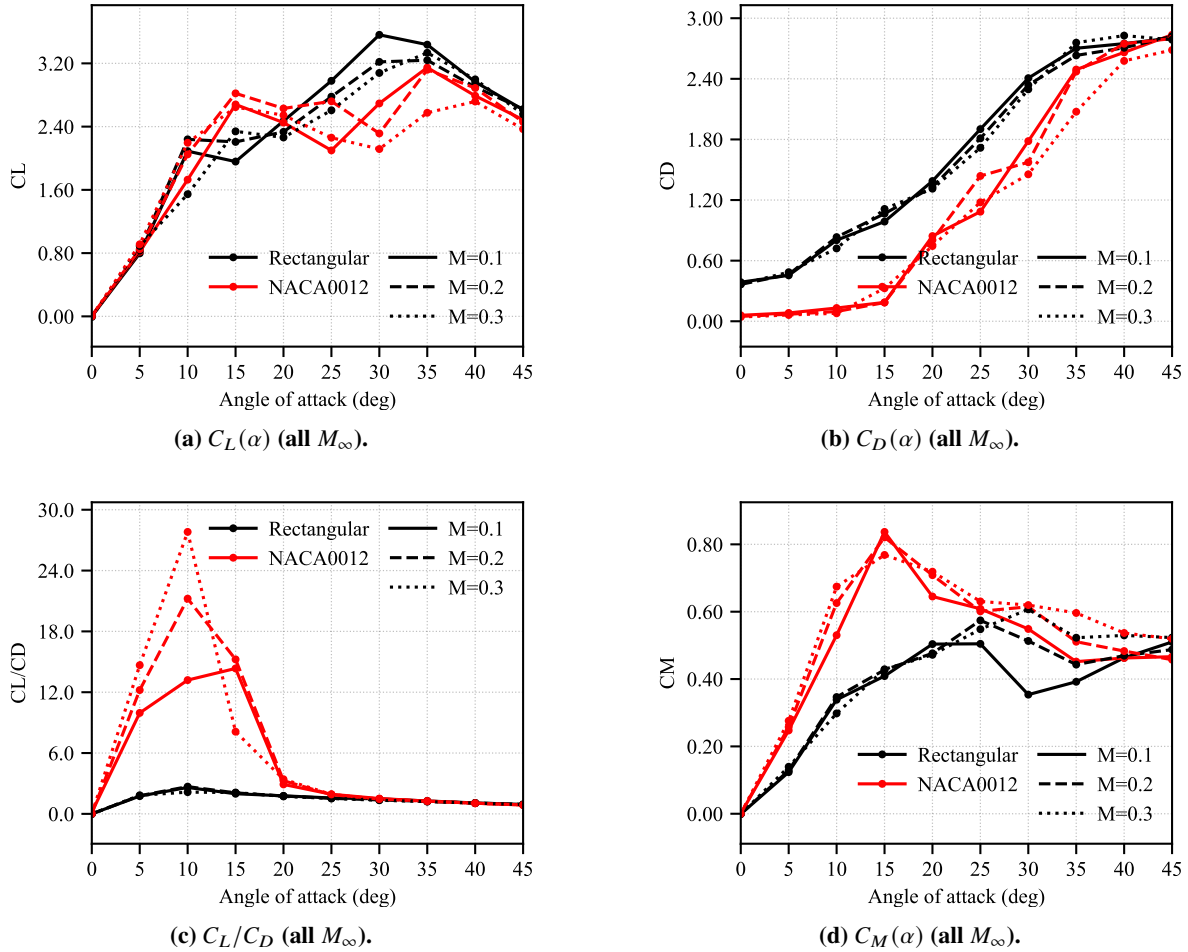


Fig. 4 Rectangular cross-section versus NACA 0012: integrated stack coefficients versus AoA α .

Compared to the rectangular struts, the streamlined NACA 0012 design mainly reduces separation-driven wake thickening and gap losses, yielding lower drag and higher lift efficiency before the interference transition constrains lift

growth. Both the rectangular-member and NACA 0012-member configurations exhibit an approximately linear increase in C_L at low angles of attack, followed by a clear transition near $\alpha \approx 15^\circ$ into an interference-dominated regime in which upstream separation thickens wakes, downstream members become increasingly shielded, and gap/blockage effects govern the incremental force response [11]. Beyond this onset, additional incidence yields less predictable lift growth: the NACA 0012 case exhibits a more pronounced C_L plateau indicating earlier saturation of integrated lift in the stacked environment. Despite similar lift levels prior to onset, the NACA 0012 maintains substantially lower parasitic drag C_D than the rectangular design over most of the pre-stall range, which drives a higher aerodynamic efficiency C_L/C_D with a peak typically occurring at moderate incidence ($\sim 5^\circ$ – 15°) and generally improving at higher Reynolds number. The NACA 0012 also yields higher C_M over most angles of attack, with the largest differences near $\alpha \approx 10^\circ$ – 20° . This shows center-of-pressure shifts as interference redistributes stack loading, and greater commanded torque to hold attitude through the transition band [12, 13].

B. Leading-Edge Radius Effects

This subsection isolates the impact of leading-edge (LE) radius scaling by comparing the LE variants $0.5\times$ and $2\times$ across angle of attack (AoA) α and freestream Mach number M_∞ . To highlight the incremental effect of LE radius, Fig. 5 reports baseline-subtracted coefficients, $\Delta C \equiv C_{\text{variant}} - C_{\text{NACA0012}}$, computed at matching (M_∞, α) .

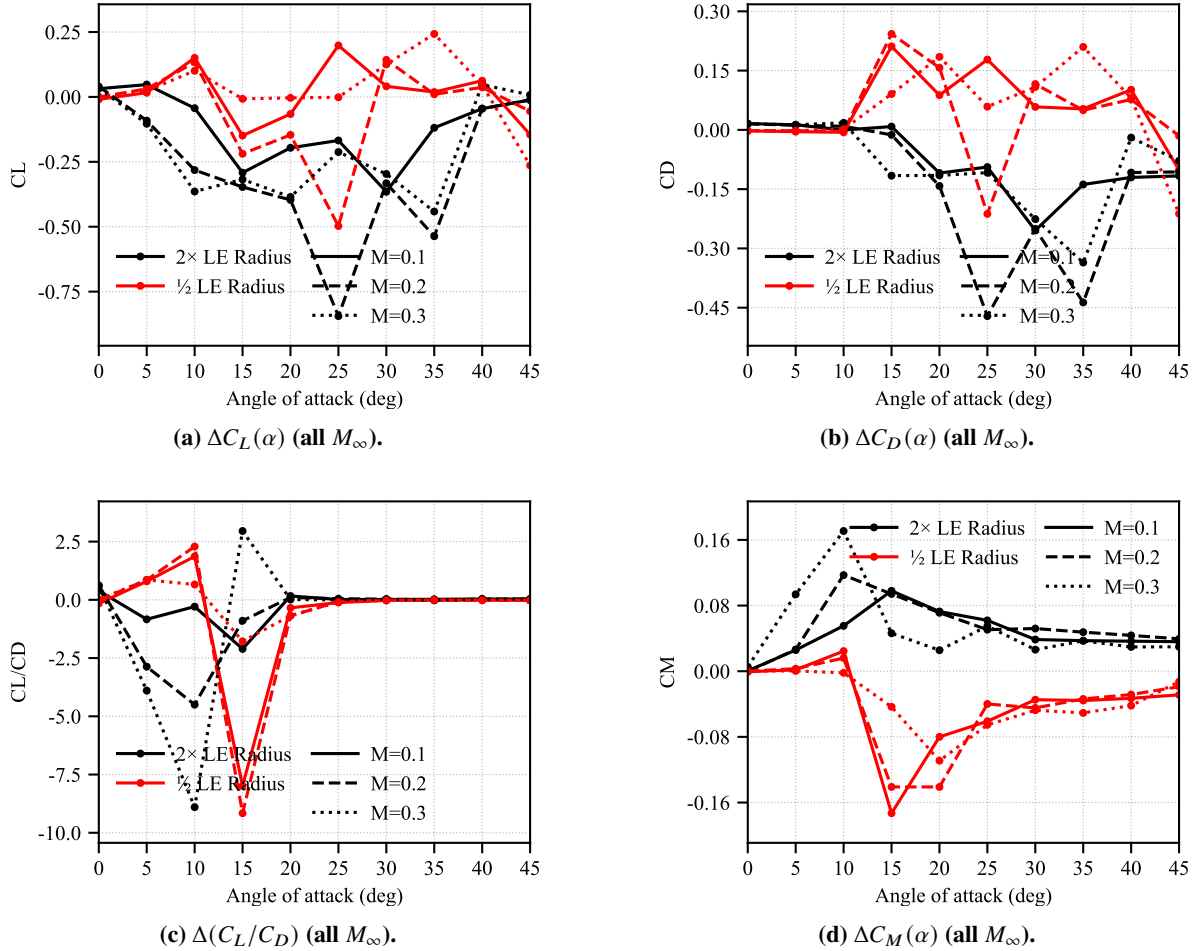


Fig. 5 LE radius comparison (baseline-subtracted): $\Delta C \equiv C_{\text{variant}} - C_{\text{NACA0012}}$ versus AoA α for LE $0.5\times$ and LE $2\times$, with $M_\infty = 0.1, 0.2, 0.3$ overlaid.

Fig. 5 shows that leading-edge (LE) radius primarily reshapes stall progression through the interference-onset region rather than providing uniform efficiency gains. Relative to the NACA 0012 baseline, both LE-scaled stacks

underperformed across much of 0° to 20° in most metrics, but they differ in how rapidly they enter and progress through the transition. The $2\times$ LE radius case exhibits a smoother onset and more gradual post-onset roll-off, especially at lower Re , whereas the $0.5\times$ LE radius case transitions more abruptly. This difference is reflected in C_L/C_D : the $2\times$ case shows a broader, shallower efficiency dip through onset, while the $0.5\times$ case exhibits a sharper, deeper drop. The pitching-moment trends indicate that increasing LE radius increases $|C_M|$ as α grows. This is consistent with redistributed nose loading in which a blunter leading edge broadens the stagnation region and weakens the peak suction/pressure gradients near the front of the member, shifting the center of pressure upstream as incidence increases [12, 14].

C. Maximum-Thickness Location Effects

This subsection examines the effect of shifting the location of maximum thickness by comparing the thickness variants $x_t/c = 0.25$ and $x_t/c = 0.35$ across AoA α and freestream Mach number M_∞ . Fig. 6 reports baseline-subtracted coefficients, $\Delta C \equiv C_{\text{variant}} - C_{\text{NACA0012}}$, computed at matching (M_∞, α) to isolate the incremental effect of shifting x_t/c .

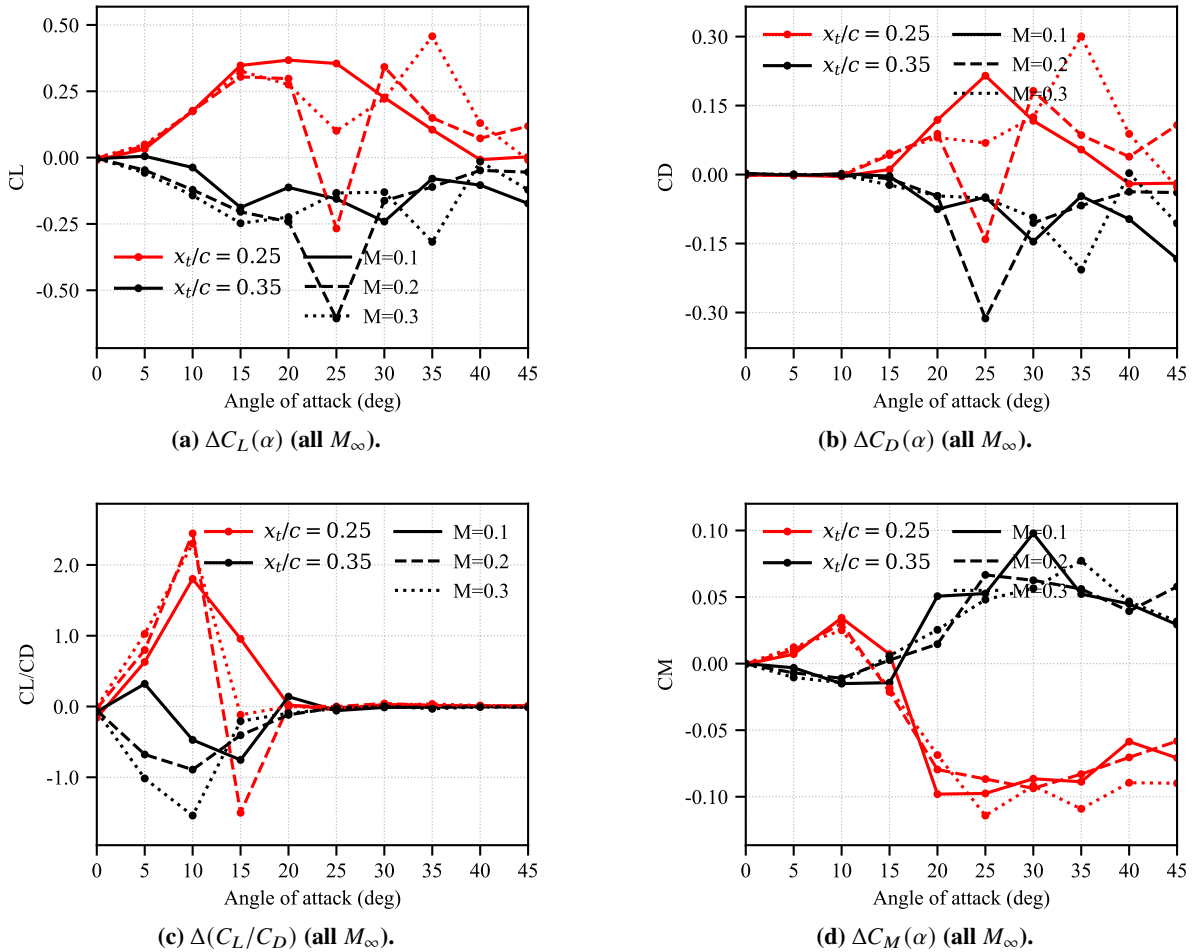


Fig. 6 x_t/c comparison (baseline-subtracted): $\Delta C \equiv C_{\text{variant}} - C_{\text{NACA0012}}$ versus AoA α for $x_t/c = 0.25$ and $x_t/c = 0.35$, with $M_\infty = 0.1, 0.2, 0.3$ overlaid.

Fig. 6 indicates that shifting the maximum-thickness location controls a peak-efficiency versus robustness tradeoff across angle of attack. In the attached-flow regime ($\sim 5^\circ$ – 12°), the forward-thick configuration ($x_t/c = 0.25$) produces positive ΔC_L and the largest gains in $\Delta(C_L/C_D)$. As α approaches and passes into the interference-dominated transition band ($\sim 15^\circ$ – 25°), the forward-thick case exhibits a sharper post-onset reduction in $\Delta(C_L/C_D)$ accompanied by drag growth, indicating that its pre-onset gains are offset by stronger penalties once wake interaction and separation intensify.

The aft-thick configuration ($x_t/c = 0.35$) yields smaller peak efficiency gains at moderate α , but it degrades more gradually through the transition region. Thickness placement also alters pitching moment beyond onset: ΔC_M trends negative for $x_t/c = 0.25$ and trends positive for $x_t/c = 0.35$, indicating a shift in how loading is redistributed within the stack at elevated incidence. Overall, moving thickness forward enhances pre-onset efficiency but steepens post-onset losses, whereas moving thickness aft reduces peak gains while improving robustness across the AoA sweep.

D. Stall Onset and Stall Angle Metrics

A stall angle α_{stall} is extracted for each case, defined as the AoA at peak C_L . The onset of stall-like nonlinearity is also compared using an onset angle α_{on} , defined as the AoA at the first local maximum of C_L . Because the CFD sweep is sampled in 5° increments, both angles are obtained by fitting a smooth function to $C_L(\alpha)$ and extracting the corresponding extrema from the fitted curve. Reported values therefore carry an effective angular uncertainty of approximately $\pm 2.5^\circ$ due to the underlying AoA discretizations.

Geometry	$M_\infty = 0.1$		$M_\infty = 0.2$		$M_\infty = 0.3$	
	α_{on}	α_{stall}	α_{on}	α_{stall}	α_{on}	α_{stall}
Rectangle	11.2	32.1	11.8	33.1	17.5	33.6
NACA 0012 (baseline)	16.0	35.0	18.8	37.3	16.6	38.4
LE radius 0.5×	16.1	35.6	15.8	37.0	16.0	37.5
LE radius 2×	16.4	36.5	16.1	39.5	16.4	42.2
$x_t/c = 0.25$	16.3	34.4	16.4	36.4	16.4	37.2
$x_t/c = 0.35$	16.2	35.9	16.6	37.2	16.1	41.0

Table 2 Interpolated stall-onset angle α_{on} (first local maximum of C_L) and stall angle α_{stall} (AoA at peak C_L) for each geometry and freestream Mach number, extracted from a fitted $C_L(\alpha)$ curve.

In general, the stall metrics show modest variation in stall-onset behavior across the airfoil-based designs, alongside clearer geometry and Mach-driven shifts in the maximum stall limit. Table 2 quantifies these regime changes by separating the onset of nonlinearity (α_{on}) from the maximum stall angle (α_{stall}). For a given M_∞ , α_{on} clusters across geometries (typically within a few degrees), consistent with a common interference threshold that is only weakly shifted by member shape. In contrast, α_{stall} is substantially more geometry-dependent. Replacing rectangular members with NACA 0012 increases both α_{on} and α_{stall} indicating that streamlined members delay the cascade-wide transition into the fully separated, blockage-dominated state [15]. Across the Mach sweep, α_{stall} generally increases with M_∞ for most geometries due to a higher Reynolds number delaying separation in the stacked environment. Geometric modifications primarily act on α_{stall} : increasing LE radius tends to raise α_{stall} (most clearly at higher M_∞), and forward thickness shifting can also increase α_{stall} (notably at $M_\infty = 0.3$) [16]. Thus, the table supports a two-level picture in which α_{on} reflects a largely interference-set transition, while α_{stall} can be pushed higher by separation-robust member geometries.

E. Flowfield Interpretation and Inter-Element Interference ($M_\infty = 0.2$)

To connect the integrated coefficient trends to the underlying stacked-flow physics, velocity magnitude contours and per-member lift redistribution are examined for the same representative cases at $M_\infty = 0.2$. Two angles of attack (AoA) are selected to contrast a low-AoA attached-flow regime ($\alpha = 10^\circ$) with an elevated-AoA interference/separation regime ($\alpha = 30^\circ$). Three geometries are compared: the rectangular baseline, the NACA 0012 baseline, and the representative modified profile ($x_t/c = 0.25$).

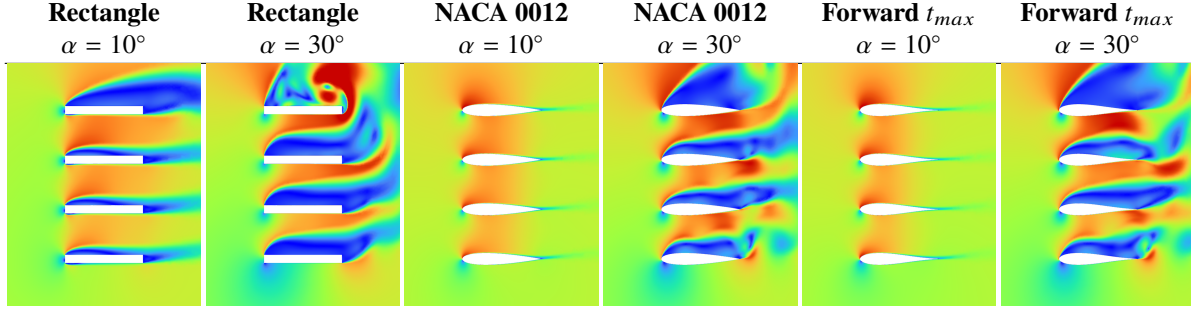


Table 3 Velocity magnitude contours at $M_\infty = 0.2$ comparing three geometries at $\alpha = 10^\circ$ and $\alpha = 30^\circ$. A common colorbar range is used across all panels to enable qualitative comparison.

Flow contours provide direct visualization of the attached and separated regimes, shown in Table 3. At $\alpha = 10^\circ$, all three geometries remain attached, but the rectangular configuration exhibits a broader wake and stronger gap jets, while the airfoil-based stacks maintain narrower wakes with more uniform penetration through the inter-member gaps. At $\alpha = 30^\circ$, separation on the upstream members produces wake expansion and downstream shielding, with the rectangular case showing pronounced blockage and impingement into the downstream gaps. On the other hand, both airfoil configurations reduce shielding and preserve partial gap flow, consistent with the delayed onset and slower post-onset degradation observed in the integrated coefficients.

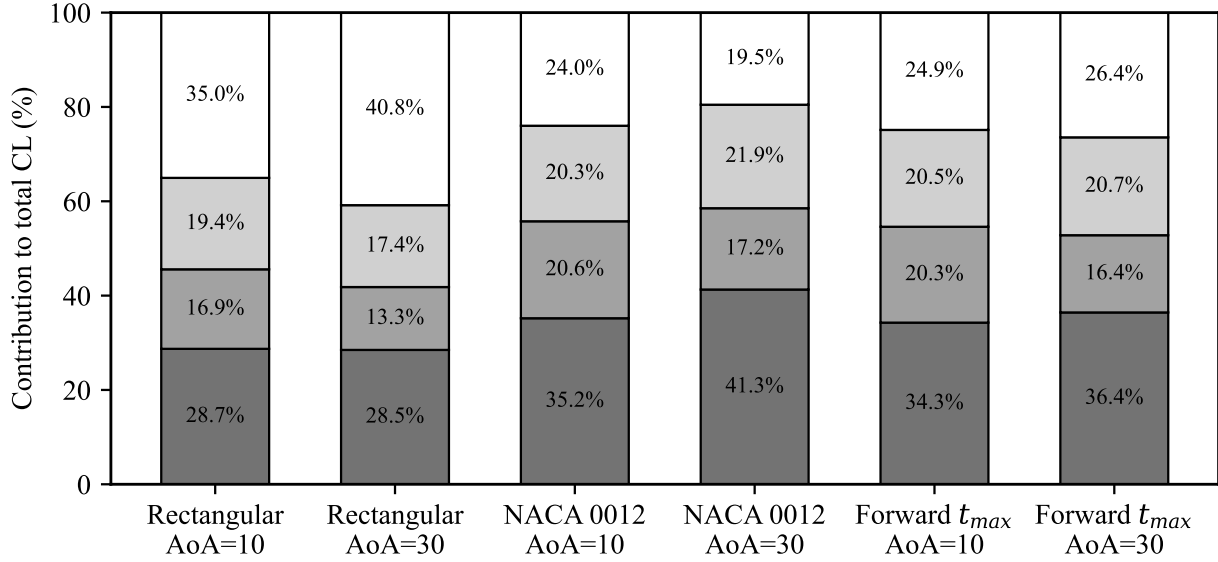


Fig. 7 Normalized per-member lift contributions $C_{L,i}/C_{L,stack}$ at $M_\infty = 0.2$ for $\alpha = 10^\circ$ and $\alpha = 30^\circ$. Segments are arranged in the same order as the physical stack: the uppermost segment corresponds to the top strut, etc.

In Fig.7 the per-member lift distributions show that the airfoil-based grid-fin designs maintain a more even member-to-member lift split than the rectangular baseline, indicating reduced interference-driven load collapse onto a single member. At $\alpha = 10^\circ$, the rectangular stack already exhibits an uneven split, with the top member contributing $\sim 35\%$ of total C_L . Conversely, both airfoil-based stacks place a larger fraction on the bottom member ($\sim 34\text{--}35\%$), consistent with the more uniform gap flow observed in the contours. At $\alpha = 30^\circ$, the rectangular and NACA 0012 stacks begin concentrating lift toward one end of the stack. The forward- t_{max} geometry moderates this redistribution (top $\sim 26\%$, bottom $\sim 36\%$) relative to NACA 0012 (top $\sim 20\%$, bottom $\sim 41\%$). More even lift sharing reduces sensitivity to single-member separation and helps preserve integrated C_L and C_L/C_D deeper into the high- α regime.

V. Conclusion

This study evaluated how grid-fin lattice member cross-section geometry influences stacked aerodynamic performance in subsonic flow. A rectangular baseline and a symmetric NACA 0012 baseline were compared, along with leading-edge (LE) radius scaling and maximum-thickness location shifting. Unsteady Reynolds-averaged Navier–Stokes (URANS) CFD sweeps were performed over $\alpha = 0^\circ\text{--}45^\circ$ and $M_\infty = 0.1\text{--}0.3$, and integrated stack coefficients (C_L , C_D , C_L/C_D , C_M) were used to quantify performance tradeoffs and operational envelope.

A. Key Findings

- **Baseline cross-section replacement (rectangle vs. NACA 0012).** Replacing rectangular struts with a symmetric airfoil profile significantly reduces parasitic drag across the pre-stall regime and increases aerodynamic efficiency (C_L/C_D). The NACA 0012 configuration achieves substantially higher peak efficiency at moderate angles of attack (approximately $5^\circ\text{--}15^\circ$) without reducing lift magnitude. Stall onset (α_{on}) occurs earlier for the rectangular geometry, and its stall angle (α_{stall}) remains the lowest across all Mach numbers tested.
- **Leading-edge radius effects.** Leading-edge radius scaling primarily influences high-angle-of-attack behavior and stall progression. Increasing LE radius ($2\times$ case) produces the largest increase in α_{stall} , reaching 42.2° at $M_\infty = 0.3$, the highest among all geometries. However, efficiency trends depend on Mach number and angle of attack: larger LE radius can improve pre-onset performance at higher M_∞ but may introduce post-onset penalties. The effect is therefore envelope-oriented (stall delay and peak lift extension) rather than uniformly efficiency-enhancing.
- **Maximum-thickness location shifting (x_t/c).** Shifting maximum thickness primarily adjusts load distribution and post-onset drag growth rather than dramatically altering stall angle. The forward-thick configuration ($x_t/c = 0.25$) improves downstream member loading at elevated α , reducing wake shielding and delaying rapid efficiency collapse. The aft-thick case ($x_t/c = 0.35$) exhibits larger drag growth beyond stall. Thickness location therefore functions as a parameter that reshapes interference behavior rather than fundamentally shifting stall onset.
- **Stall metrics and nonlinearity.** For airfoil-based geometries, stall-onset angle α_{on} remains clustered near $16^\circ\text{--}18^\circ$ across Mach numbers, indicating that early nonlinearity is largely governed by stacked-member interference rather than isolated airfoil stall. In contrast, α_{stall} varies more significantly with geometry, especially for LE scaling. The rectangular configuration consistently exhibits the lowest α_{stall} .
- **Inter-element interference as the dominant high- α mechanism.** Flowfield contours and per-member lift redistribution demonstrate that high-angle-of-attack performance degradation is governed by upstream wake expansion and downstream shielding. Geometries that maintain narrower wakes and more uniform lift sharing (e.g., the forward-thick configuration) delay severe efficiency collapse. Thus, stacked interference controls the elevated α regime.

B. Practical Implications

Adopting symmetric airfoil cross-sections in place of rectangular struts provides the most direct and impactful performance improvement, reducing parasitic drag and substantially increasing aerodynamic efficiency in the pre-stall operating range without diminishing lift authority. In order to extend high-angle controllability or delay stall, increasing leading-edge radius increases α_{stall} and extends the peak-lift envelope, particularly at higher Mach numbers within the tested range. Adjusting maximum-thickness location tunes wake interaction and downstream load redistribution within the stack. Forward-thick configurations improve load sharing and mitigate severe efficiency collapse at elevated angles of attack, while aft-thick configurations incur stronger post-stall drag penalties. Because elevated-angle performance is governed primarily by inter-element interference rather than isolated airfoil characteristics, cross-sectional choices should be evaluated at the stacked-lattice level when defining operational envelopes.

C. Limitations and Future Work

The present study models a two-dimensional (2D) representation of a fundamentally three-dimensional (3D) grid-fin lattice; finite-span effects, frame interactions, and true lattice topology are not captured. In addition, URANS with a transition model can reproduce comparative trends but may not fully resolve strongly separated, unsteady wake dynamics that dominate at elevated α . The lattice pitch/blockage configuration was fixed, and no sensitivity study was performed on prescribed inflow turbulence parameters. No formal grid-convergence or time-step sensitivity study was conducted to bound coefficient uncertainty. The discrete 5° AoA sampling necessitates fitted interpolation for

α_{on} and α_{stall} , introducing uncertainty in extracted stall/nonlinearity metrics, and the investigated Mach range remains limited to $M_{\infty} = 0.1\text{--}0.3$. Future work should therefore include grid and time-step refinement studies, extension to 3D grid-fin segments (including frame effects and lattice topology), broader parameter sweeps (e.g., additional g/c (gap), blockage ratio, and member count) to quantify interference scaling, expansion to higher Mach and transonic regimes, and validation of selected cases via wind-tunnel testing and/or higher-fidelity simulation methods such as DES/LES.

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