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Reduction of Rotor Noise Using Serrated Blades with Modulated Airfoil Thickness

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ABSTRACT

This paper investigates the effects of blade serrations with spanwise airfoil thickness modulation on rotor noise, with emphasis on two recently identified noise sources: trailing-edge vortex-shedding (TE-VS) noise and blade secondary vortex interaction (BSVI) noise. High-fidelity computational fluid dynamics simulations are performed for a hovering Ideally Twisted Rotor using NASA’s OVERFLOW solver with Delayed Detached Eddy Simulation, and far-field acoustic predictions are obtained via PSU-WOPWOP. Two trailing-edge serration geometries are examined: cut-in serrations, in which the trailing edge follows a sinusoidal profile, and add-on serrations, in which a sawtooth pattern is appended to the baseline trailing edge. For each geometry, the effect of spanwise airfoil thickness modulation is assessed. The modulated cut-in serration is found to be the most effective configuration for suppressing TE-VS noise, achieving a pronounced spectral rolloff beyond 10 kHz. Flow visualization confirms that the serration geometry disrupts the spanwise coherence of the Kármán vortex street by generating streamwise vortices and spanwise pressure gradients, thereby fragmenting the periodic shedding pattern. However, this high-frequency benefit comes at the cost of increased BSVI noise in the mid-frequency range, driven by a more energetic wake shear layer and stronger secondary vortex formation. The simultaneous application of cut-in serrations to both the leading and trailing edges is shown to mitigate this trade-off, reducing mid-frequency BSVI noise penalty while preserving TE-VS suppression. A serration parameter study further demonstrates that the acoustic results are not greatly sensitive to variations in serration height and wavelength within the range tested.

INTRODUCTION

Rotor aeromechanics has become a rapidly growing field driven by increasing interest in Unmanned Aerial Vehicles (UAVs) and Urban Air Mobility (UAM). While these new vehicle concepts are technically feasible and socially viable, federal regulations and public acceptance remain major barriers to their widespread implementation, particularly with respect to noise. Aerodynamically generated rotor noise is broadly classified into two main categories: tonal noise and broadband noise. Tonal noise arises from deterministic sources, including periodic blade motion and aerodynamic loading, whereas broadband noise originates from turbulent flow structures and other unsteady aerodynamic mechanisms. For UAVs and UAM vehicles, broadband noise is of particular concern owing to its strong presence in the mid- to high-frequency range, which is especially perceptible and annoying to human listeners. The broadband class itself encompasses several distinct components, including blade-wake interaction (BWI) noise, turbulence ingestion noise, and airfoil-self noise.

Recently, Won and Lee (Refs. 1–3) identified and characterized two previously unreported rotor noise sources. The first is trailing-edge vortex-shedding (TE-VS) noise in rotating blades, which is amplified by the proximity of a preceding tip vortex to the blade trailing edge. For blades with blunt

trailing edges of finite thickness, the separated shear layers emanating from the pressure and suction sides roll up into alternating vortical structures, forming the canonical Kármán vortex street. This vortex shedding is further amplified when a preceding tip vortex closely interacts with the trailing edge, generating distinct tonal humps in the high-frequency spectrum (Ref. 1). The second newly identified source is blade secondary vortex interaction (BSVI) noise, which originates from the wake shear layer (WSL) generated by the preceding rotor blade. As the WSL rolls up into a tip vortex, its development is influenced by the tip vortex shed during the previous revolution, resulting in an S-shaped vortex pattern between the two vortex cores (Refs. 4–6). These S-shaped vortices, which are embedded within turbulent wakes, are irregularly spaced. When these irregularly spaced secondary vortices interact with the blade, they induce unsteady pressure fluctuations and generate quasi-tonal noise (Refs. 2, 3). Although this quasi-tonal component emerges as a residual from phase-averaged pressure fluctuations, it manifests at harmonics of the blade passing frequency (BPF). This noise source contributes primarily to the mid-frequency range, although further investigation is needed to fully characterize their behavior.

Various studies have investigated methods to reduce rotor noise. One effective approach is the use of serrated trailing edges, which has been shown to significantly attenuate turbulent boundary layer trailing-edge noise (TBL-TE)

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noise (Refs. 7–10). In the present work, we extend the application of trailing-edge serrations to target additional noise sources, including TE–VS noise. In addition to trailing-edge serrations, we introduce a modulated airfoil thickness distribution, in which the local thickness varies along the span in accordance with the chord-length variations imposed by the serration geometry. This spanwise modulation is expected to enhance local three-dimensional flow effects, thereby weakening the TE–VS mechanism and its associated noise. Furthermore, we examine the influence of serrated trailing edges with modulated airfoil thickness on BSVI noise in the mid-frequency range.

High-fidelity computational fluid dynamics (CFD) simulations are employed to accomplish these objectives. The CFD approach enables direct interrogation of the underlying physical mechanisms responsible for noise reduction, while also permitting a systematic evaluation of the effects of serration geometry parameters on acoustic performance. The findings of this study are expected to contribute meaningfully to the development of quieter rotorcraft, thereby supporting broader efforts to reduce noise pollution and advance the environmental sustainability of aviation technologies.

METHODS

Geometry

We use the Ideally Twisted Rotor (ITR) as our benchmark case, originally tested by Pettingill et al. (Ref. 11). This rotor consists of four blades and employs a modified NACA 0012 airfoil with a trailing-edge thickness of 0.50 mm. It has a radius of 0.1588 m and a constant chord length of 0.0318 m. The twist distribution follows a hyperbolic profile, with a root angle of 34.5° and a tip angle of 6.9° . Under the baseline operating condition of 5500 RPM, the rotor produces a measured thrust coefficient of 0.0123. These parameters correspond to a tip Reynolds number of approximately 2.0×10^5 and a tip Mach number of 0.267. The rotor characteristics and operating conditions are shown in Tables 1 and 2, respectively.

Table 1: Rotor characteristics.

Ideally Twisted Rotor	
Radius	0.1588 m
Chord length	0.0318 m
Tip twist	6.9°
Solidity	0.255
Number of blades	4
Airfoil	modified NACA 0012
Tip planform	rectangular

Table 2: Operating conditions.

Hover tip Mach number	0.27
Angular Velocity	5500 RPM
Rotor thrust coefficient	0.0137

Serrations are applied from 75% of the radial span to the rotor blade tip, as shown in Fig. 1. The two key serration parameters are the *serration height* ($2h$) and the *serration wavelength* (λ), both of which are non-dimensionalized by the chord length.

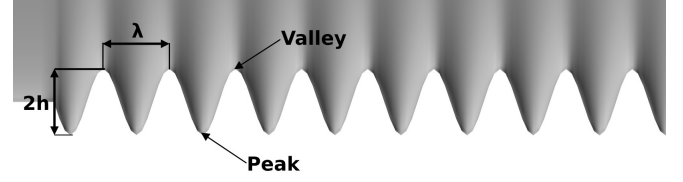


Fig. 1: Serrated geometry near the trailing edge.

Two serration geometries are investigated in the present study. The first is a cut-in serration, in which the trailing edge follows a sinusoidal profile that oscillates between peaks and valleys. The second is an add-on serration, in which a saw-tooth pattern is appended directly to the baseline trailing edge. Based on experimental evidence, add-on serrations are generally easier to manufacture and integrate onto propeller blades (Ref. 9). Figure 2 shows the baseline, cut-in, and add-on serrations.

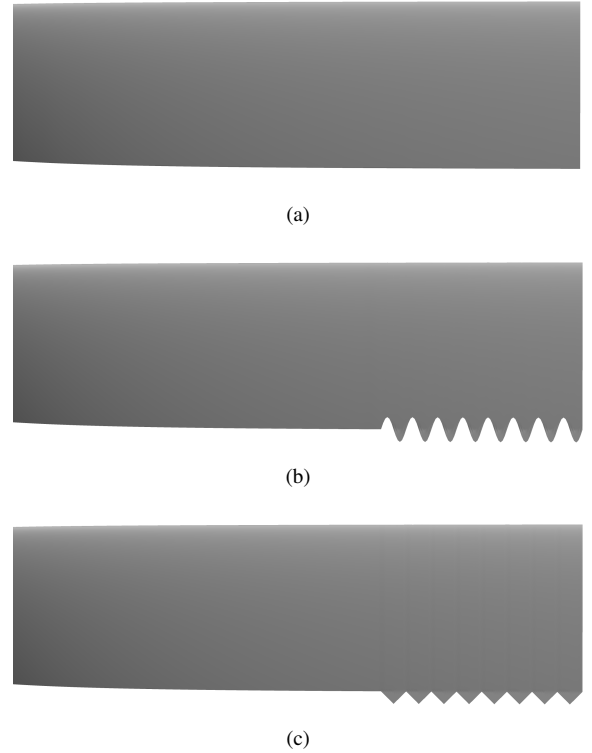


Fig. 2: Comparison of baseline and two trailing-edge serration geometries: a) Baseline, b) Cut-in, and c) Add-on.

For the cut-in serration, the peaks and valleys of the serrated geometry are generated by scaling the airfoil section, resulting in variations in chord length. As the chord length changes, the airfoil thickness varies at each radial station with the same scaling along the rotor blade, resulting in the modulated airfoil

thickness in the spanwise, as shown in Fig. 3. These geometric variations are expected to play an important role in explaining the noise reduction discussed in this paper.

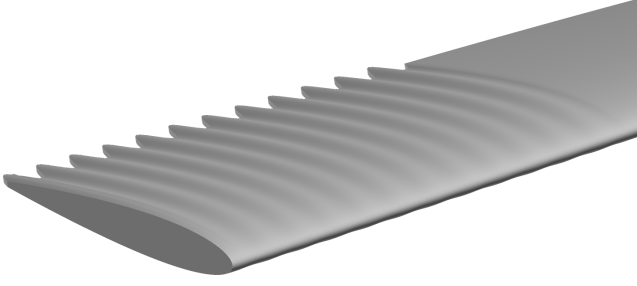


Fig. 3: Modulated airfoil thickness with trailing-edge cut-in serrations.

CFD Mesh

An overset mesh strategy is used. The near-body (NB) grids are created using the Chimera Grid Tools v2.1 (OVERGRID) software package to capture boundary layer flow physics (Ref. 12). As shown in Fig. 4, the mesh is structured with three O-grids per blade, consisting of a main grid, a root cap, and a tip cap grid. The baseline main grid contains $277 \times 242 \times 87$ points along the chordwise, radial, and body-normal directions, respectively. Uniform grids were added near the tip of the blade to replicate how serrated meshes were generated. The trailing edge is discretized with 29 grid points and rounded using the smoothing operation. To preserve the serrated trailing-edge geometry, each serration uses 12 airfoil stations, resulting in an enlarged grid of $277 \times 242 \times 87$ points. The wall-normal direction extends one chord length from the surface, with a maximum stretching ratio of 1.104 in the first half of the chord. Beyond this region, a uniform spacing (Δs) equal to 2.5% of the tip chord (C_{tip}) is applied, where hole cutting and fringe point interpolation occur. The first-cell height is 1.1×10^{-6} m, corresponding to $y^+ \approx 0.33$ based on the tip velocity, and the total number of NB grid points (all four blade meshes combined) is approximately 22.62 million. Table 3 shows the detailed mesh statistics for the baseline and serrated blades, as well as the computational cost.

A Cartesian off-body (OB) grid is automatically generated by OVERFLOW, extending $20R$ in all directions from the rotor hub. Figure 4(b) depicts the Cartesian grid, with the red box denoting the rotor region and the blue box representing the wake region. The rotor region extends from the hub to $1.25R$ in the x - and y -directions, and spans $+0.2R$ and $-0.3R$ in the z -direction, while the wake region has the same extent in the x - and y -directions but extends to $-3R$ in the z -direction. The level-(1) grid spacing is set to 10.0% of C_{tip} , with each refinement level halving the grid spacing of the previous level, and the base refinement level in the rotor region is set to -1 , corresponding to a spacing of 5.0% of C_{tip} . Outside the rotor region, the grid gradually coarsened, maintaining a minimum buffer of 8 grid points between refinement levels.

Adaptive mesh refinement (AMR) is applied to both the rotor and wake regions but was activated only after a 10-revolution quick-start procedure. The refinement is guided by a sensor function based on the undivided maximum difference of conserved quantities (e.g., density, momentum, and energy), with the adaptation threshold set to the default value discussed by Buning and Pulliam (Ref. 13). In the rotor region, AMR is allowed to refine down to level -2 , corresponding to a spacing of 2.5% of C_{tip} , which is necessary to capture blade tip vortices and near-wake turbulence, while in the wake region the minimum refinement level is set to 1 (i.e., 10.0% of C_{tip}), ensuring a relatively coarse mesh to reduce computational cost, as only surface pressures and near-rotor turbulence are relevant for far-field noise predictions.

Table 3: Computational mesh and cost.

Near-body grid	Baseline	Serrated
Blade	5.8 mil	5.8 mil
Tip Cap	1.5 mil	1.1 mil
Root Cap	1.5 mil	2.3 mil
Off-body grid		
AMR OFF	6.7 mil	6.7 mil
AMR ON	25.5 mil	24.5 mil
Total grid		
AMR OFF	41.9 mil	43.5 mil
AMR ON	60.4 mil	61.4 mil
Number of processors	384	384
Simulation time (h)	78.2	64.8

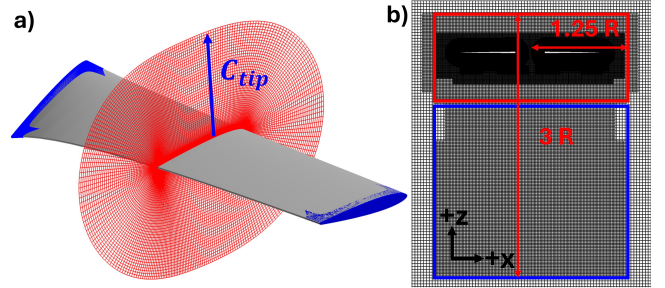


Fig. 4: CFD mesh: a) near-body grids and b) off-body grids.

CFD Simulation

NASA's OVERFLOW 2.4c solver is employed for high-fidelity CFD simulations, utilizing structured overset grids to solve the compressible Navier–Stokes equations (Ref. 14). The code is particularly well suited for simulating unsteady, turbulent flows around complex geometries and has been widely applied to rotorcraft aerodynamic and aeroacoustic predictions (Refs. 15–17). OVERFLOW can operate in either a finite-difference or finite-volume framework and supports both RANS and DDES turbulence models. In the present study, we employ DDES with a fifth-order mapped Weighted Essentially Non-Oscillatory (WENOM) scheme combined with the improved Harten–Lax–van Leer–Einfeldt (HLLC++)

approximate Riemann solver for inviscid flux calculations. Previous studies have shown that the HLLC++ solver with WENOM reconstruction provides reduced numerical diffusion compared to central differencing (Ref. 18). Viscous fluxes, however, are computed using the standard second-order central scheme.

A dual-time stepping approach is employed, where the physical time is advanced using an optimized second-order backward differencing scheme. To accelerate convergence, the improved implicit symmetric successive over-relaxation solver is adopted. Although this approach is not as efficient as central differencing with the diagonalized Beam–Warming pentadiagonal solver, it achieves lower residuals with fewer subiterations. In practice, the right-hand-side L_2 -norm residuals are reduced by at least two orders of magnitude within 10–15 subiterations for each physical time step.

A quick-start procedure is implemented in which the initial ten rotor revolutions are simulated with a temporal resolution of 2.5° per time step. For the seven subsequent revolutions, a significantly finer resolution of 0.25° per time step is employed, with AMR activated every two time steps (i.e., every 0.5°). Surface pressures from each blade mesh and volume data from the main grid of a single blade are stored at the same frequency as the AMR adaptation.

Acoustic Post-processing

Acoustic predictions are performed using PSU-WOPWOP (Refs. 19–21), which solves Farassat’s Formulation 1A (Ref. 22) of the Ffowcs Williams–Hawkins (FW–H) equation (Ref. 23). Aperiodic impermeable surface pressures from each blade are supplied to PSU-WOPWOP after a ten-revolution quick-start, recorded at every other time step (0.5°), yielding a Nyquist frequency of 66 kHz. The last six revolution data are used for aperiodic acoustic computations. The distance of a single observer relative to the rotor hub is 2.27 m (14.29R), with an elevation angle of 35° . This observer location corresponds to the microphone location five in the experiment (Ref. 11).

RESULTS

Acoustic Validation

Figure 5 shows the narrowband sound pressure level (SPL) with a bandwidth of 20 Hz for the measurements, along with the predictions for the baseline. These results are similar to other computational studies for the ITR case (Ref. 24). It is shown that the baseline case matches well with the experimental data, capturing the first BPF peak, BSVI quasi-tones at mid frequency, and the TE–VS beyond 10 kHz. While the baseline case slightly deviates from the measurement, the primary flow physics of interest are captured by the simulation. Given the grid and temporal spacing, we also have confidence in our CFD predictions up to 20 kHz.

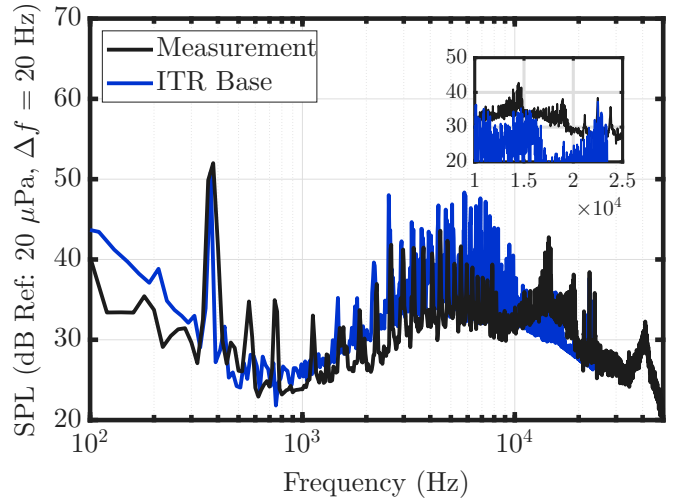


Fig. 5: Narrowband SPL comparison at microphone 5 for the measurement along with predictions for the baseline case.

Acoustics from Various Serration Geometries

Serration height and width studies are conducted for the modulated cut-in serration geometry and are presented in the appendix. The noise results are found to be insensitive to these parameters. However, Ning et al. noted that larger trailing-edge serrations demonstrate more noise reduction benefits when serration heights are increased (Ref. 10). In accordance to this information, a serration height of $0.15c$ and a serration wavelength of $0.15c$ are selected for the detailed noise analysis of the various serration configurations examined in this paper.

Figure 6 presents the one-third octave band SPL spectra for the three cases. The add-on serration case closely follows the baseline across the full frequency range. For the cut-in serration case, the SPL is elevated relative to the other cases near 12.7 kHz; however, a pronounced reduction at higher frequencies indicates effective suppression of TE–VS noise. Both serrated cases exhibit a moderate increase in the mid-frequency range, which may be attributed to additional wake unsteadiness introduced by the serration geometry.

We next introduce spanwise thickness modulation in the serration region to promote three-dimensional flow effects. For the add-on serration cases, thickness modulation produces a slight increase in SPL across the mid- and high-frequency ranges, as shown in Fig. 7(a). For the cut-in cases, thickness modulation yields a sharper spectral rolloff beyond 10 kHz (Fig. 7(b)), demonstrating its effectiveness in attenuating noise in the frequency range dominated by TE–VS. Despite this high-frequency benefit, the modified geometry produces a substantial increase in the mid-frequency range, which is associated with BSVI noise. This suggests that spanwise thickness modulation strengthens three-dimensional flow effects in a manner that intensifies BSVI events. Figure 7(c) compares all modulated cases — including add-on serrations, cut-in serrations, and no serrations — against the baseline. The modulated blade without serrations substantially amplifies high-frequency TE–VS noise, confirming that thickness modula-

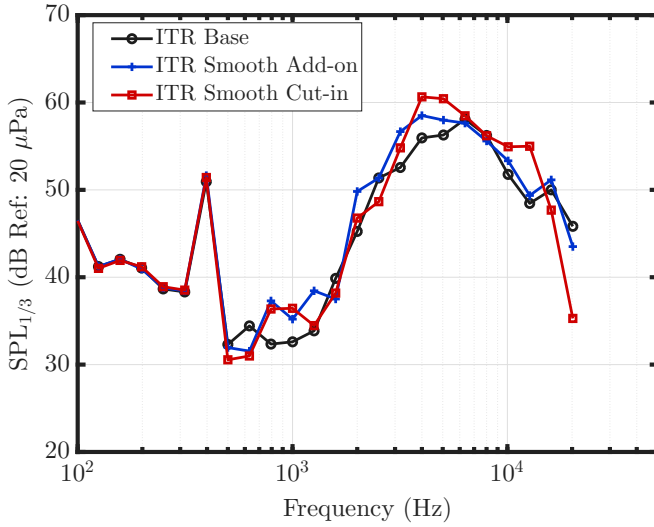


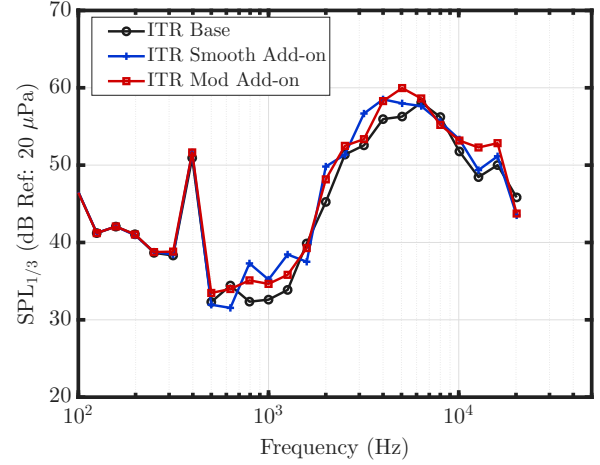
Fig. 6: One-third octave band SPL comparison at microphone 5 for the baseline, smooth add-on, and smooth cut-in case.

tion alone is insufficient and must be paired with an appropriate trailing-edge geometry. Among all configurations, the modulated cut-in serration is the most effective at suppressing TE-VS noise; however, this benefit comes at the cost of an increased mid-frequency BSVI noise contribution.

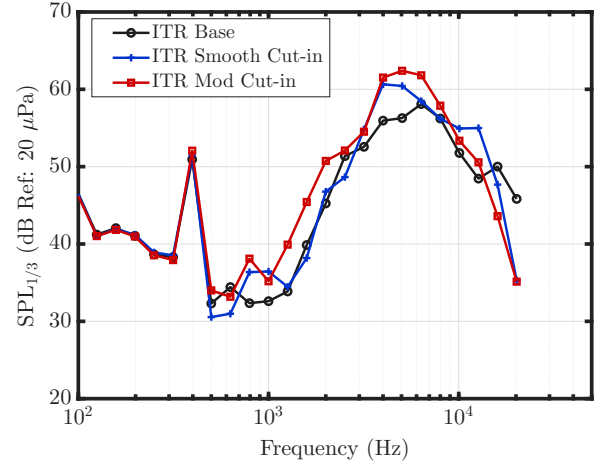
Given that the cut-in serration with modulated thickness yielded the most favorable results for TE-VS noise reduction, an analogous serration geometry was also applied to the leading edge. Prior studies have demonstrated the effectiveness of leading-edge serrations in mitigating broadband noise as well as primary blade-vortex interaction (BVI) noise, suggesting a potential to similarly target BSVI noise (Refs. 25–28). Figure 8 shows that both serrated geometries produce comparable SPLs up to 5 kHz. Nevertheless, a notable overall reduction in the 5–10 kHz frequency range as well as a similar noise reduction at high frequency are observed for the leading-edge serration case, although a slight increase at 12.7 kHz. Taken together, these results reveal a trade-off between BSVI noise and TE-VS noise reduction that depends on the specific serration geometry employed.

Flow Physics and Noise Source Identification

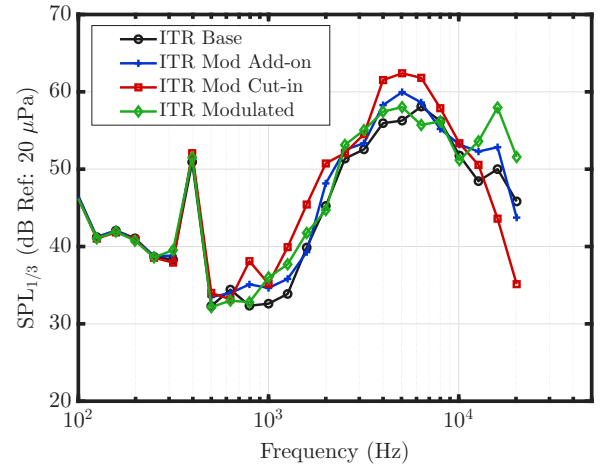
The implementation of trailing-edge serrations effectively mitigates TE-VS noise, as demonstrated in Figs. 6 and 7. In this subsection, the flow physics behind this noise reduction is further investigated. Figure 9 presents iso-surfaces of the Q-criterion in the near-wake region behind the trailing edge near the blade tip, comparing the baseline and modulated cut-in serration configurations. In the baseline case, TE-VS is clearly evident, driven by the influence of the preceding tip vortex passing in close proximity to the trailing edge and amplifying the local upwash velocity (Ref. 1). In the serrated case, vortex shedding is substantially suppressed in the peak regions of the serration. In the valley regions, TE-VS persists; however, the coherent periodic shedding pattern observed in the baseline is largely disrupted.



(a)



(b)



(c)

Fig. 7: One-third octave band SPL comparison at microphone 5 between a) add-on cases, b) cut-in cases, and c) all modulated cases.

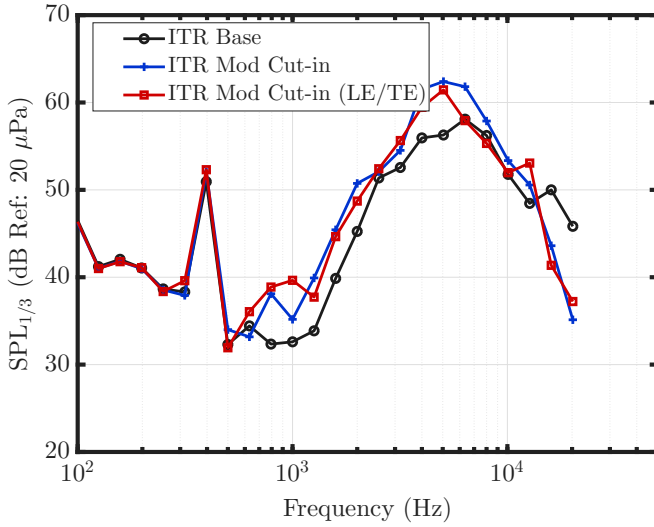


Fig. 8: One-third octave band SPL comparison at microphone 5 between baseline case, modulated cut-in serrations at TE, and modulated cut-in serrations at LE and TE.

Figure 10 presents the spanwise (z -direction) vorticity for the baseline and modulated cut-in serration cases, plotted on a common scale. The vorticity magnitude is noticeably elevated in the serrated case, indicating stronger vortical structures in the blade wake. These intensified vortical flows promote the development of a more energetic WSL, which subsequently rolls up into the tip vortex and gives rise to more pronounced secondary vortices. Consequently, an increase in BSVI noise at mid frequencies is expected for the serrated case, consistent with the spectral results presented in Fig. 7.

Figure 11 presents the spanwise (z -direction) vorticity extracted at the mid-chord location along the span. In the serrated case, not only is the vorticity magnitude substantially elevated, but alternating signs of vorticity are also induced by the spanwise thickness modulation of the airfoil. This alternating pattern is a hallmark of three-dimensional vortical structures, confirming that the modulated geometry promotes three-dimensional flow effects in the blade wake.

The three-dimensional flow structures associated with the serrated case are clearly visualized in Fig. 12, which presents surface streamlines (oil-flow patterns) together with the surface pressure gradient from mid-span to the blade tip. The baseline configuration exhibits a predominantly uniform flow field throughout this region, with notable deviations confined to the vicinity of the blade tip. In contrast, the modulated cut-in serration case displays distinctly three-dimensional flow structures localized to the region where the serrations are applied, confirming that the combination of spanwise thickness modulation and trailing-edge serrations plays a central role in promoting spanwise variability in the near wake. In the baseline case, a pronounced pressure-gradient variation is observed at the trailing edge near the outboard section, driven by TE-VS. In the modulated serrated case, pressure-gradient variations are clearly distributed along the span, with elevated magnitudes at the serration peaks and reduced magnitudes at the valleys, a direct consequence of the spanwise airfoil thick-

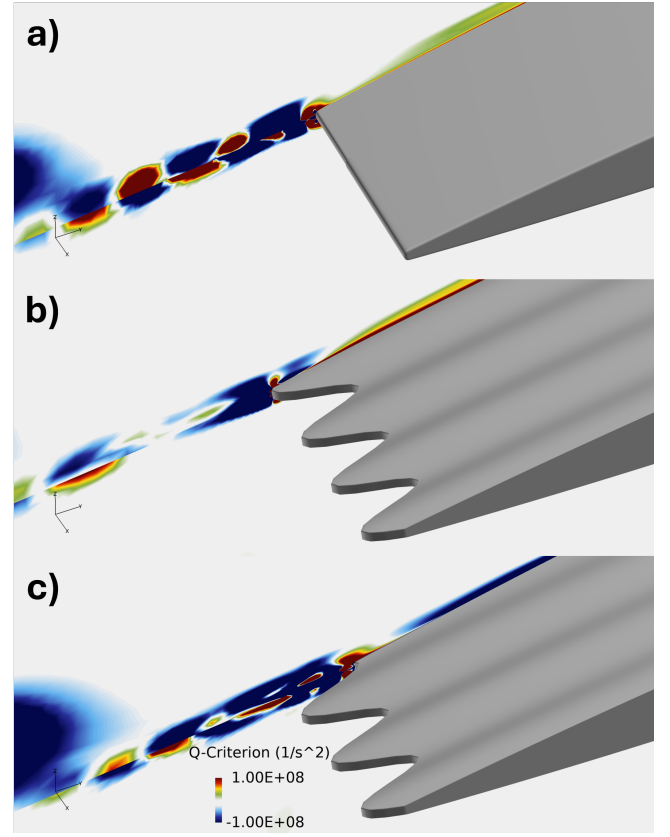


Fig. 9: Chordwise view of Q-Criterion behind the trailing edge near the blade tip: a) baseline, b) serration peak, and c) serration valley for the modulated cut-in serration.

ness modulation. This modulation-induced spanwise pressure gradient acts as the primary driver of the observed three-dimensional flow behavior.

In two-dimensional simulations, vortex shedding manifests as a perfectly periodic, spanwise-infinite vortex train because no spanwise variation exists to disrupt coherence. In physical three-dimensional flows, however, vortices are shed continuously along the trailing-edge span, and when the geometry remains uniform and the incoming turbulence is weak, the shed vortices retain strong spanwise coherence, producing intense tonal shedding—particularly when the local upwash velocity is enhanced by a passing tip vortex. The introduction of trailing-edge serrations and spanwise airfoil thickness modulation disrupts this coherence by generating three-dimensional disturbances, including streamwise vortices and spanwise pressure gradients. These disturbances shorten the spanwise correlation length, causing vortices to shed at slightly different phases or frequencies along the span. As a result, the roll-up process becomes disordered, and the Kármán vortex street loses its spanwise uniformity, giving rise to fragmented and distorted vortex structures. The associated unsteady surface pressure fluctuations near the trailing edge are consequently attenuated. In summary, blunt trailing-edge vortex shedding requires large-scale spanwise coherence to produce strong periodic aerodynamic forces, and the three-dimensional perturbations induced by trailing-edge serrations and thickness

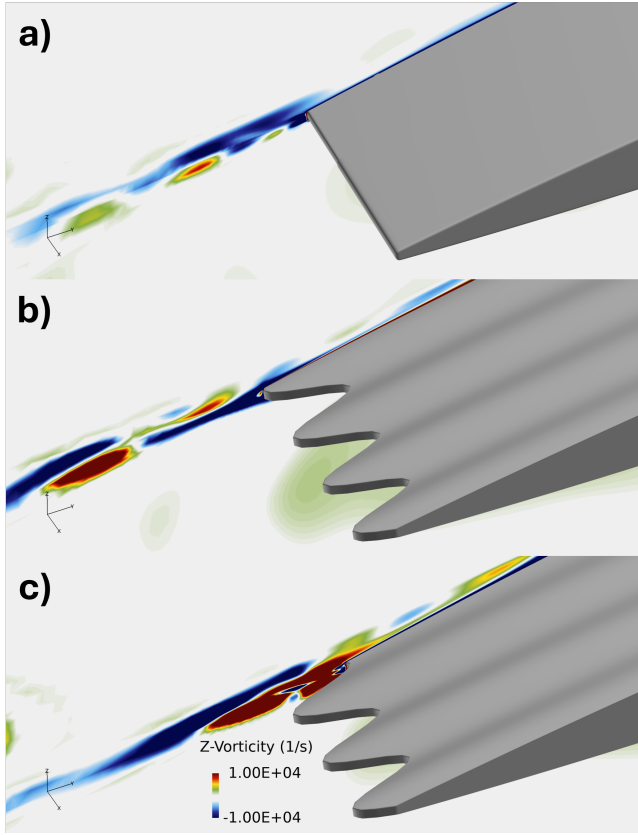


Fig. 10: Chordwise View of dimensional z-vorticity: a) baseline b) serration peak and c) serration valley for the modulated cut-in serration.

modulation introduce sufficient spanwise variability to fragment the wake and significantly weaken the TE–VS mechanism.

An instantaneous snapshot of the baseline blade loading noise integrand is examined at an azimuthal angle of 315° in Fig. 13(a). Near the leading edge, the figure reveals a localized region of negative and positive loading, which is attributed to BSVI arising from the impingement of a secondary tip vortex on the blade surface. Pressure spillover at the blade tip is evidenced by the light blue shading in that region. Near the trailing edge, alternating positive and negative pressure regions indicate pressure fluctuations induced by the blunt trailing edge, consistent with the TE–VS mechanism.

The remaining blade configurations are shown in Fig. 13(b)–(f). For the smooth add-on serration cases (Fig. 13(b)), TE–VS is suppressed at the outer serration peaks but intensified at the inner serrations, resulting in a net noise penalty. In contrast, modulated cut-in serrations (Fig. 13(e)) more effectively attenuate TE–VS noise through a combination of three-dimensional flow effects and turbulence breakdown mechanisms. Nevertheless, all four surface contour plots exhibit localized regions of elevated loading along the chordwise direction of the blade. These are attributed to wake modifications that strengthen BSVI events, increasing noise in the mid-frequency range. This effect is most pronounced for the modulated thickness cut-in serration case (Fig. 13(e)), where

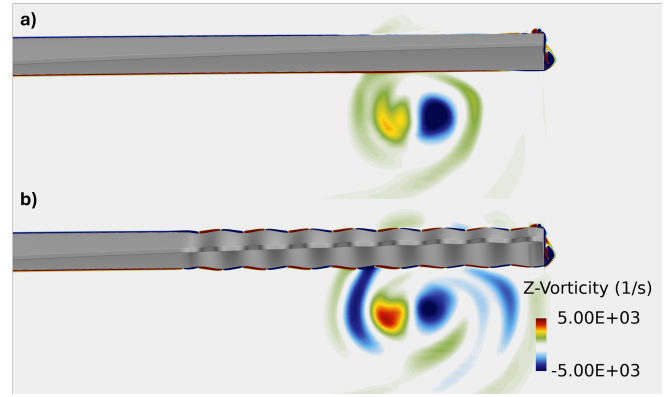


Fig. 11: Z-Vorticity at the mid-chord location along the blade span: a) baseline and b) cut-in serrations.

three-dimensional flow effects generate elevated loading noise in the serration valleys. When modulated cut-in leading-edge serrations are introduced (Fig. 13(f)), vortex breakdown and wake mixing become apparent, producing destructive interference effects in both the chordwise and spanwise directions.

CONCLUSIONS

This study investigated the effects of blade serrations with modulated airfoil thickness on rotor broadband noise, with particular focus on two recently identified noise sources: TE–VS noise and BSVI noise. High-fidelity CFD simulations using NASA’s OVERFLOW solver were performed for the Ideally Twisted Rotor, and acoustic predictions were obtained via PSU-WOPWOP. The following conclusions are drawn from this work.

Add-on serrations produced acoustic results comparable to the baseline across the full frequency range. Cut-in serrations with modulated airfoil thickness were identified as the most effective configuration for suppressing TE–VS noise. The modulated geometry promotes spanwise pressure gradients and streamwise vortices that shorten the spanwise correlation length of the shed vortices, disrupting the coherent Kármán vortex street and producing a pronounced spectral rolloff beyond 10 kHz. Flow visualization via Q-criterion iso-surfaces confirmed substantial suppression of vortex shedding at the serration peaks, with only residual, incoherent shedding persisting in the valleys.

However, the same geometric modifications that attenuate TE–VS noise intensify BSVI noise in the mid-frequency range. Spanwise vorticity analysis revealed that the serrated geometry substantially elevates the vorticity magnitude in the blade wake, energizing the wake shear layer, strengthening secondary vortex formation, and intensifying the resulting blade–vortex interaction events. This trade-off between TE–VS and BSVI noise was consistently observed across all serration configurations tested.

The application of analogous cut-in serrations to both the leading and trailing edges provided a more balanced noise reduction. The combined leading- and trailing-edge serration case showed a slightly reduced noise penalty in the mid-

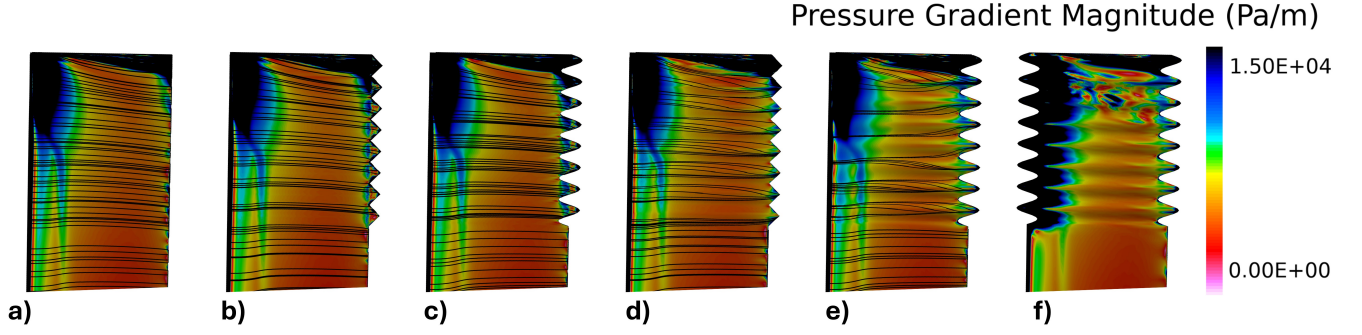


Fig. 12: Surface streamlines with the pressure gradient: a) baseline, b) smooth add-on, c) smooth cut-in, d) modulated add-on, e) modulated cut-in, f) modulated cut-in (LE/TE)

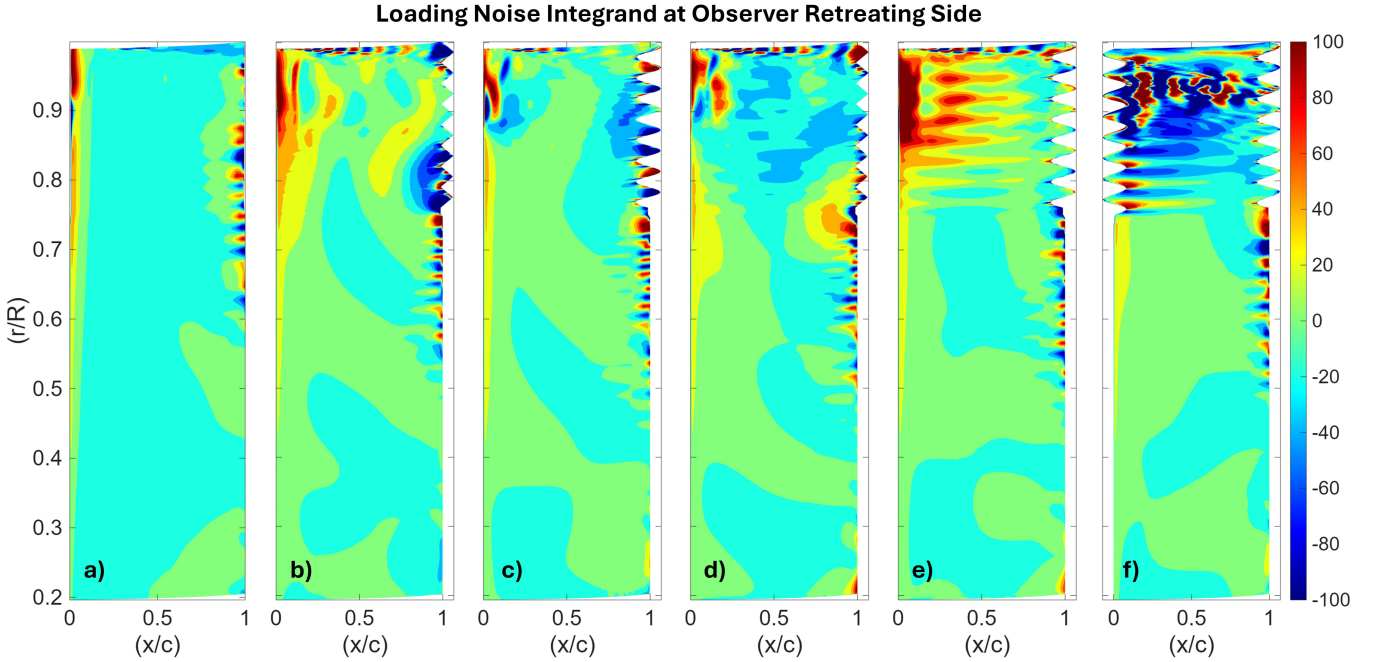


Fig. 13: Loading noise integrand surface contour plot at 315° azimuth angle: a) baseline, b) smooth add-on, c) smooth cut-in, d) modulated add-on, e) modulated cut-in, f) modulated cut-in (LE/TE)

frequency range associated with BSVI noise while maintaining the high-frequency TE–VS suppression, though a slight increase near 12.7 kHz was noted. Vortex breakdown and wake mixing introduced by the leading-edge serrations produced destructive interference effects in both the chordwise and spanwise directions, further disrupting organized noise-generating flow structures.

A serration parameter study presented in the appendix showed that the acoustic results are not very sensitive to variations in serration height and wavelength within the range tested, lending confidence to the selected baseline geometry of $2h/c = 0.15$ and $\lambda/c = 0.15$.

In future work, CFD simulations will be extended to cover a greater number of rotor revolutions at the fine temporal resolution, providing more statistically converged acoustic predictions. In addition, a systematic shape optimization study

will be conducted to identify serration geometries that simultaneously minimize both TE–VS and BSVI noise, targeting an optimal balance between high-frequency and mid-frequency noise reduction. Furthermore, the present study does not account for TBL–TE noise, which is known to be effectively attenuated by trailing-edge serrations. In future work, analytical TBL–TE noise predictions obtained from models such as UCD-QuietFly (Ref. 29) can be incorporated alongside the CFD-based results to provide a more complete broadband noise assessment of the serrated rotor configurations.

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APPENDIX A: CUT-IN SERRATION PARAMETER STUDY

In this appendix, six modulated cut-in serration geometries are considered, as shown in Fig. A.1. Each serrated case is denoted by two suffixes: the first specifies the height-to-chord ratio and the second specifies the wavelength-to-chord ratio. Although Fig. A.1 illustrates only trailing-edge serrations, leading-edge serrations are also examined. Trailing-edge serration cases are designated ITRTE, while combined leading- and trailing-edge serration cases are designated ITRLTE.

Figure A.2 presents the effect of serration height and width on the one-third octave band SPL. The first column corresponds to the ITRTE cases, the second column to the ITRLTE cases, and the third column to the difference between the two for

each configuration. A positive difference indicates that the addition of leading-edge serrations increases the SPL relative to the trailing-edge-only case, while a negative difference indicates a reduction. No consistent trend is observed across the parameter space, and the SPL results are generally similar among all cases. Some cases reduce noise at certain frequencies but increase noise at other frequencies. Based on these findings, a serration height of $0.15c$ and a serration wavelength of $0.15c$ are selected as the baseline serration geometry and analyzed in detail for the main study.

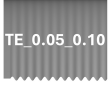
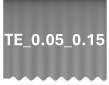
	$\lambda/c = 0.05$	$\lambda/c = 0.10$	$\lambda/c = 0.15$
$2h/c = 0.05$			
$2h/c = 0.10$	N/A		
$2h/c = 0.15$	N/A	N/A	

Fig. A.1: Trailing-edge serration test matrix.

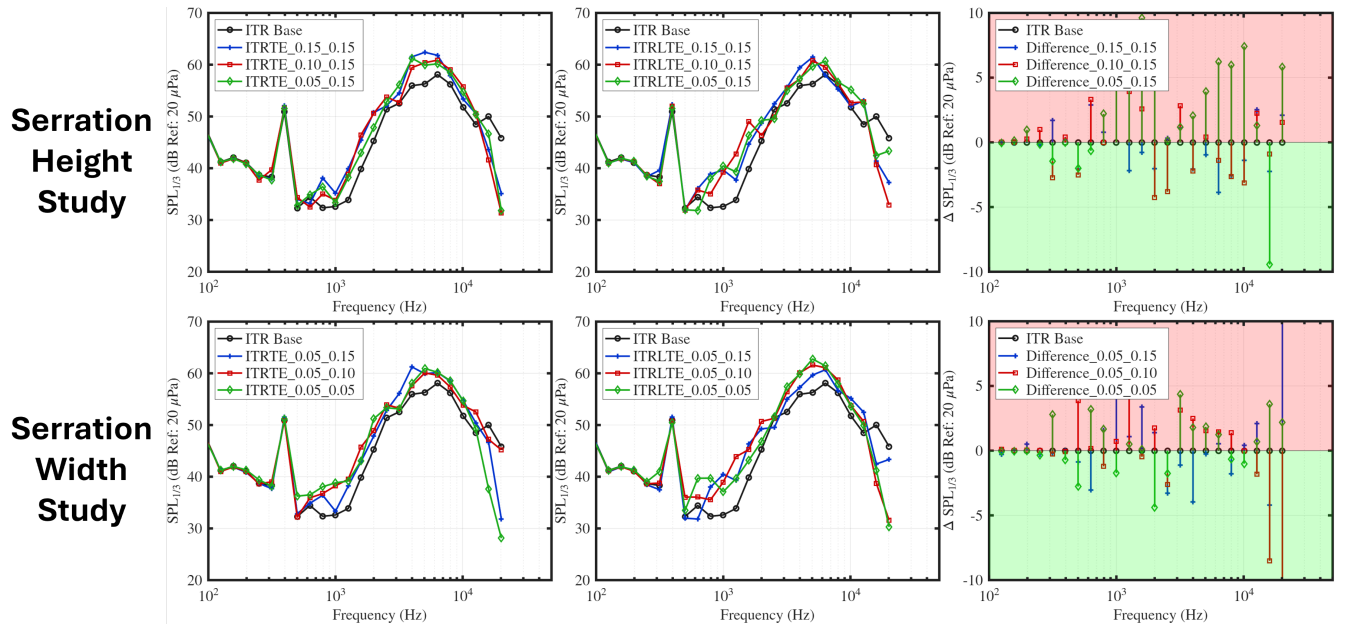


Fig. A.2: One-third octave band SPL comparison at microphone 5 for serrated trailing-edge/leading-edge parameter study.