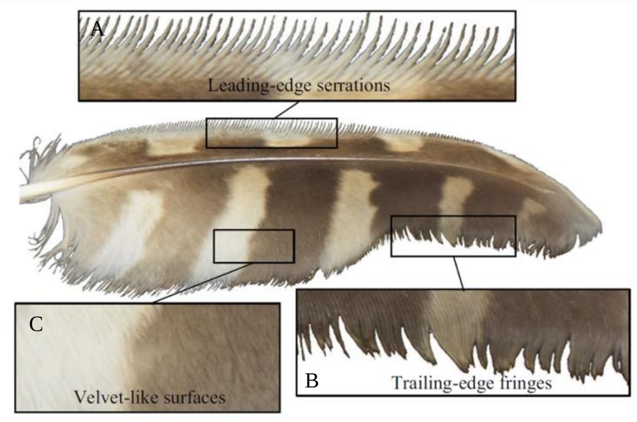
2017 International Bionic Innovation Competition

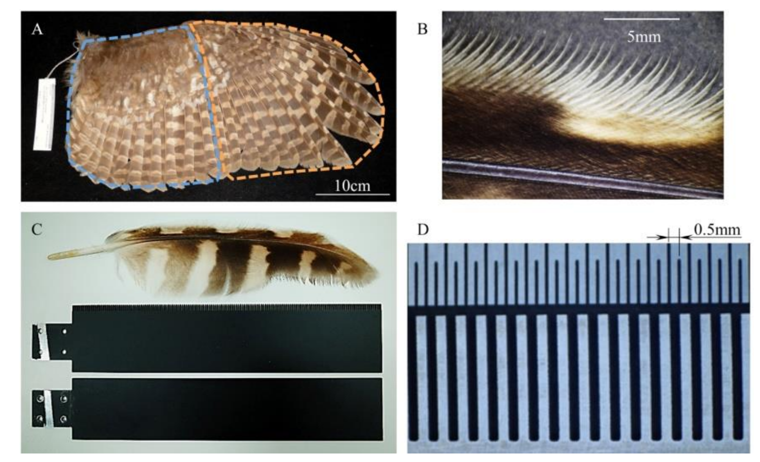
Owl's leading-edge serrations hold a key to achieve silent flight

Introduction: Owl – The Silent Hunter



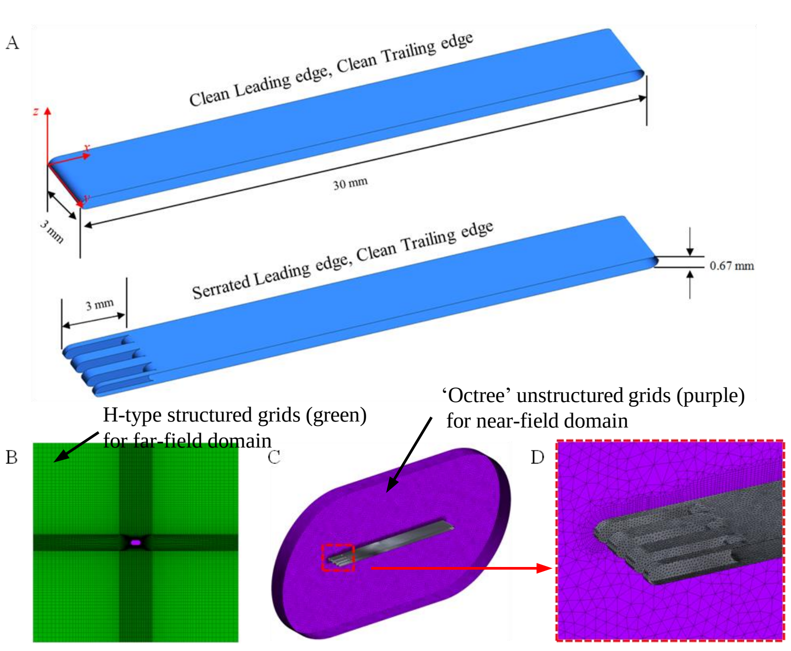
Owls are widely known for silent flight, achieving remarkably low noise gliding and flapping flights owing to their unique wing morphologies, which are normally characterized by leading-edge serrations (A), trailing-edge fringes (B) and velvet-like surfaces (C). However, how these morphological features affect aerodynamic force production and sound suppression is still not well known. Here we address an integrated study of owl-inspired wing models with and without leading-edge serrations through large-eddy simulations (LES) and wind tunnel experiments to unveil the novel mechanisms associated with tradeoff between aerodynamic force production and sound suppression.

Material: Owl-inspired single-feather wing model



(A) Right wing of a female ural owl. (B) The comb-like serrated leading-edge. (C) Owl single feather (top)-inspired wing models with serrated (middle) and clean (bottom) leading-edge. (D) Close-up view of the serrations.

Method: Large eddy simulation using WALE model



Close-up view of the grids at leading-edge

Filtered governing equations for incompressible flows

$$\frac{\partial \bar{U}_i}{\partial x_i} = 0 \qquad \frac{\partial \bar{U}_i}{\partial t} + \frac{\partial}{\partial x_j}\left(\bar{U}_i \bar{U}_j\right) = -\frac{1}{\rho}\frac{\partial \bar{p}}{\partial x_i} + \frac{\partial}{\partial x_j}\left[\nu\left(\frac{\partial \bar{U}_i}{\partial x_j} + \frac{\partial \bar{U}_j}{\partial x_i}\right)\right] - \frac{\partial \tau_{ij}}{\partial x_j}$$

subgrid-scale stress tensor τ_{ij} accounts for the influence of the filtered small scale eddies

$$\tau_{ij} = \overline{U_i U_j} - \bar{U}_i \bar{U}_j$$

an eddy-viscosity assumption to close the τ_{ij} term

$$\tau_{ij} - \frac{\delta_{ij}}{3}\tau_{kk} = -2\nu_t \bar{S}_{ij}$$

δ_{ij} the Kronecker symbol
ν_t the turbulent eddy viscosity

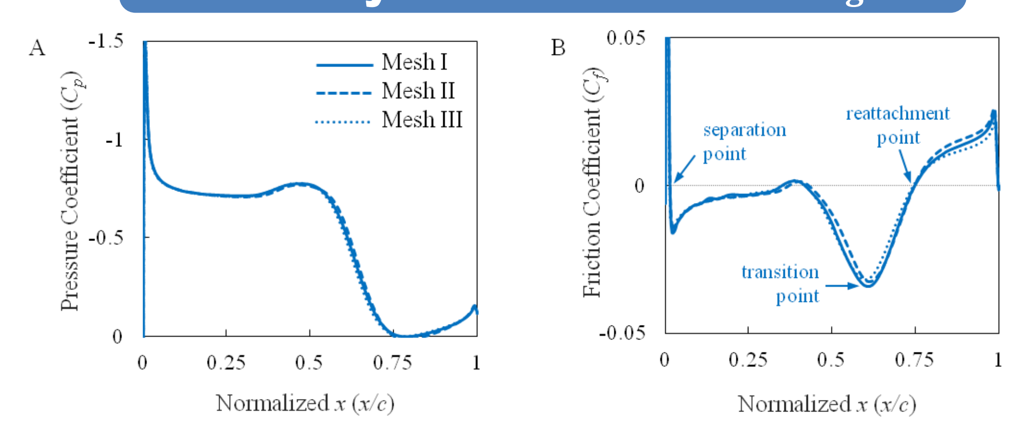
$\bar{S}_{ij}$ the strain rate tensor of the resolved field defined by

$$\bar{S}_{ij} = \frac{1}{2}\left(\frac{\partial \bar{U}_i}{\partial x_j} + \frac{\partial \bar{U}_j}{\partial x_i}\right)$$

Wall-adapted local eddy-viscosity (WALE) model

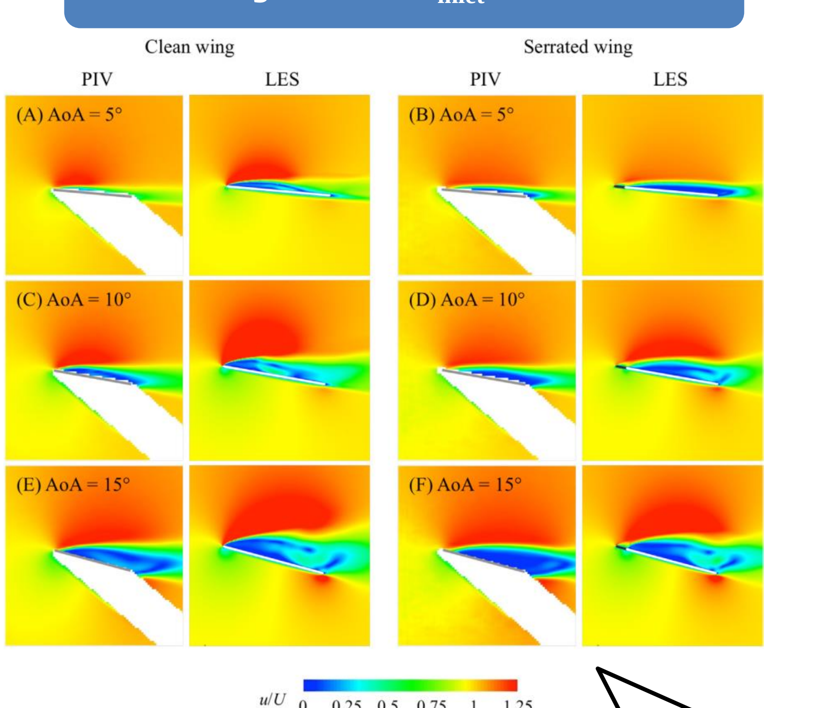
$$\nu_t = (C_w \Delta)^2 \frac{\left(S_{ij}^d S_{ij}^d\right)^{3/2}}{\left(\bar{S}_{ij}\bar{S}_{ij}\right)^{5/2} + \left(S_{ij}^d S_{ij}^d\right)^{5/4}}, \qquad S_{ij}^d = \frac{1}{2}\left(\bar{g}_{ij}^2 + \bar{g}_{ji}^2\right) - \frac{1}{3}\delta_{ij}\bar{g}_{kk}^2$$

Grid sensitivity study: clean model in steady case U = 3 m/s AoA = 5 deg

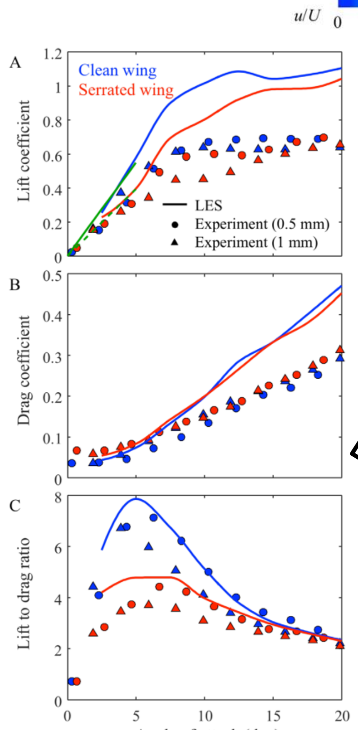


	Mesh I	Mesh II	Mesh III
Minimum grid spacing	0.025 mm	0.050 mm	0.075 mm
Node number of the inner domain	691,042	502,622	308,275
Separation position (x/c)	1.340×10^{-2}	1.358×10^{-2}	1.206×10^{-2}
Transition position (x/c)	6.058×10^{-1}	6.124×10^{-1}	5.981×10^{-1}
Reattachment position (x/c)	7.478×10^{-1}	7.461×10^{-1}	7.429×10^{-1}

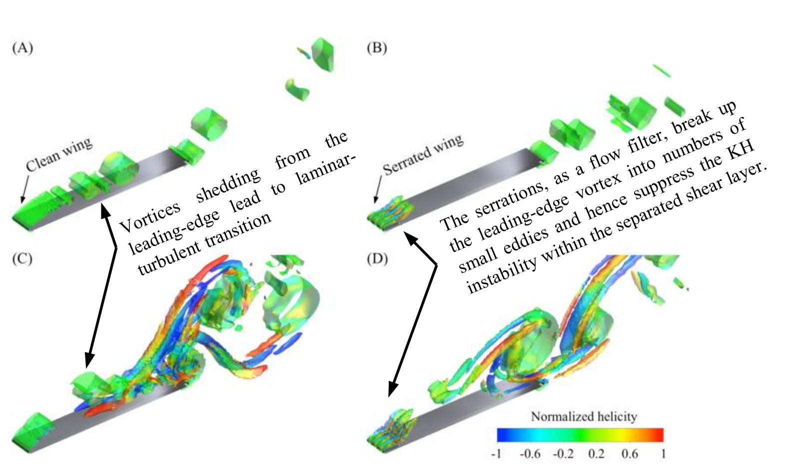
Steady case: $U_{\text{inlet}} = U$ = 3 m/s



Contours of CFD-based time-averaged velocities normalized by incoming velocity indicating that match well the PIV results, indicating that the LE-serrations passively control the flow separation. Details can be found in our recent publication [1].



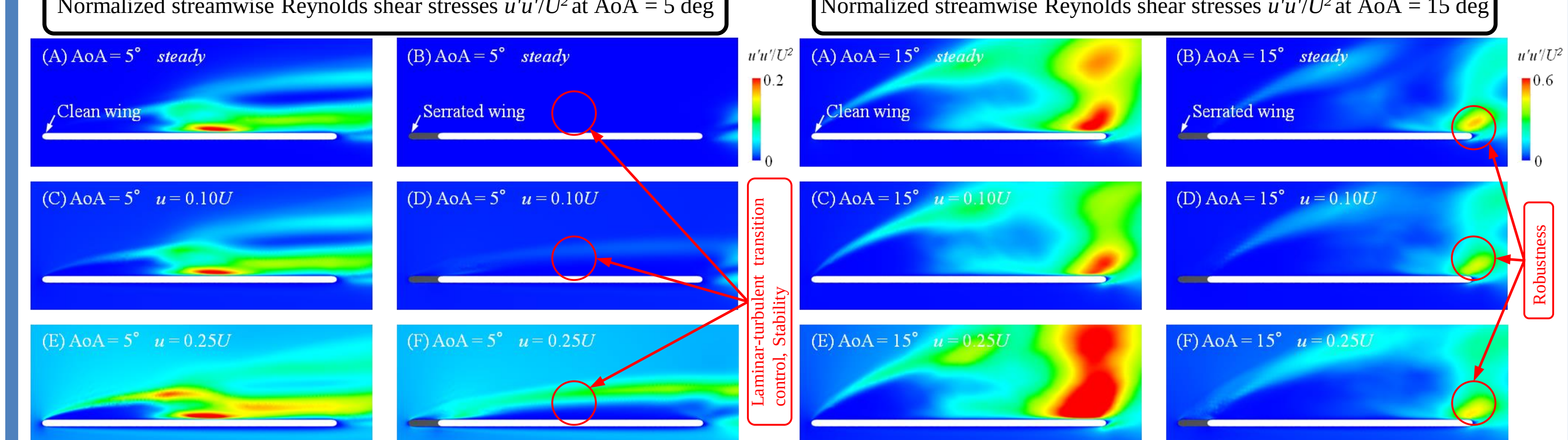
Lift-to-drag ratios are in reasonable agreement between EXP and CFD whereas both lift and drag are over-predicted in CFD due to 3D effect owing to interplay among wing tip vortex, leading-and trailing-edge vortices for low aspect ratio wings (AR = 5). Green solid line (lift-curve slope estimated by 2D thin airfoil theory) and green dashed line (lifting-line theory for 3D plate) match well the LES and EXP results, respectively, further validating the LES-based simulations.



Unsteady case: $U_{\text{inlet}} = U + u \cdot \sin(2\pi f t)$, $u = 0.10U, 0.25U, f$ = 5 Hz

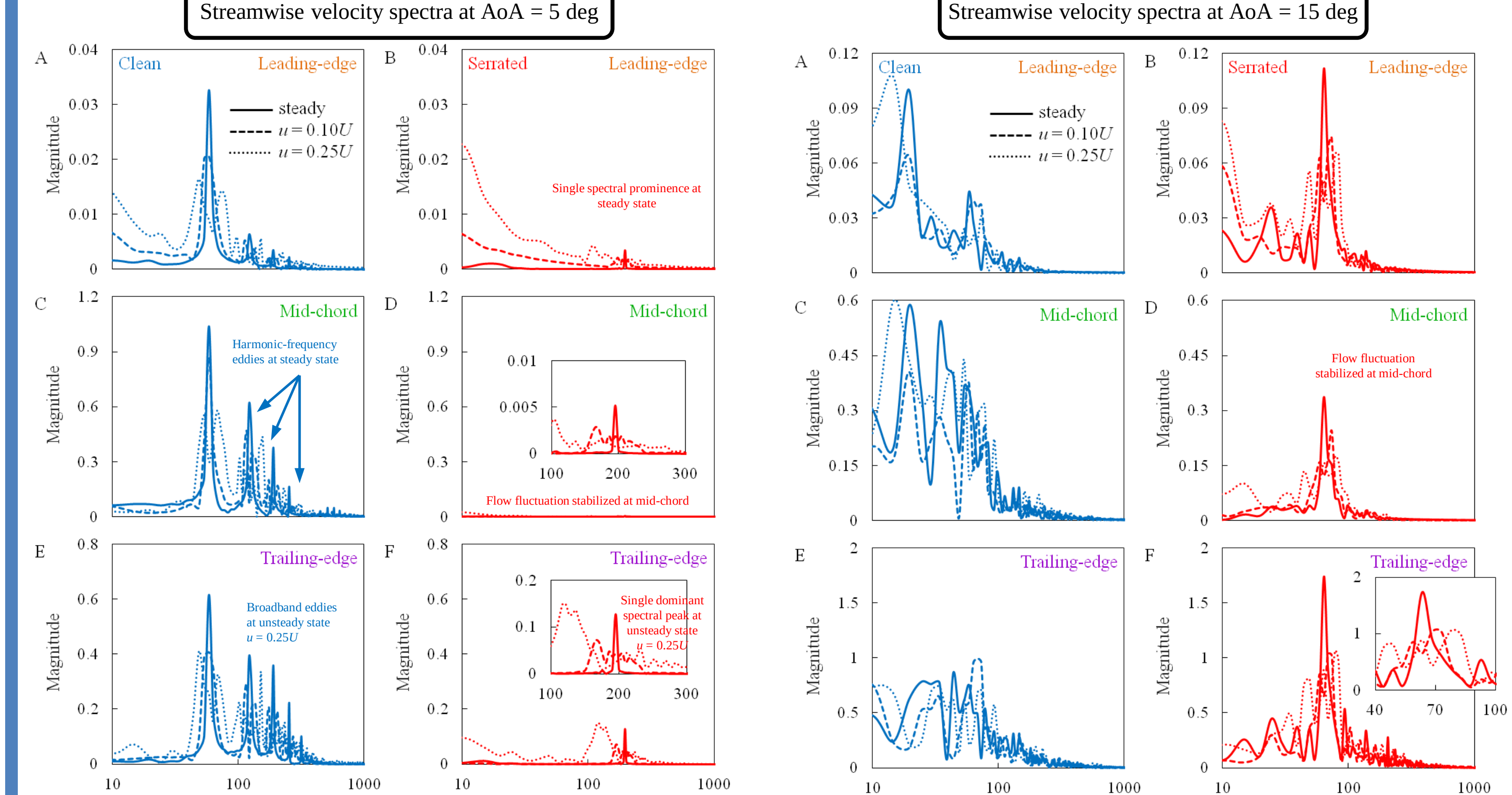
Normalized streamwise Reynolds shear stresses $u'u'/U^2$ at AoA = 5 deg

Normalized streamwise Reynolds shear stresses $u'u'/U^2$ at AoA = 15 deg



Streamwise velocity spectra at AoA = 5 deg

Streamwise velocity spectra at AoA = 15 deg



LE-serrations are capable of stabilizing the flow fluctuations due to laminar-turbulent transition and providing a robust mechanism in resolving the tradeoff between sound suppression and force production.

Conclusions

1. Leading-edge serrations, as a flow filter, can break up the leading-edge vortex into small eddies and hence suppress the KH instability within the separated shear layer.
2. Leading-edge serrations can passively control laminar-turbulent transition through stabilizing suction flow, which is robust and effective even under unsteady state in suppressing sound production.
3. Leading-edge serrations are capable of providing a strategy in resolving the tradeoff between sound suppression and force production. Compared to the clean model, the serrated wing model shows a reduction in aerodynamic force production at lower AoAs < 15 deg, but obviously a capability to achieve an even aerodynamic performance at higher AoAs > 15 deg while suppressing the noise production.
4. Owl-inspired leading-edge serrations may provide a useful device for aero-acoustic control in biomimetic rotor designs for wind turbines, aircrafts, multi-rotor drones as well as other fluid machinery.

Publication

Scan the QR code to access

[1] Chen Rao *et al* 2017 *Bioinspir. Biomim.* **12** 046008 (press released)