Study on the Aerodynamic Performance and Noise Characteristics of Several Bio-Inspired Airfoils (Postprint)

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Abstract

Based on airfoil theory, airfoils were extracted from four bird wings at the 40% spanwise section, and the flow field and acoustic field of different bionic airfoils were simulated using Large Eddy Simulation combined with the FW-H equation method of acoustic analogy. The unsteady flow field calculation results indicate that under adverse pressure gradient, flow separation initiates at the leading edge of the blade suction surface; distinct vortex structures are generated downstream of the blade, which break down after detaching from the blade trailing edge. Among the four bionic airfoils, the seagull airfoil exhibits the maximum lift-to-drag ratio, while the pigeon wing exhibits the minimum lift-to-drag ratio, yet the pigeon wing possesses excellent noise reduction characteristics. The directivity distribution of sound pressure level reveals that bionic airfoil sound sources exhibit dipole sound source characteristics.

Full Text

Numerical Study on Aerodynamic Performance and Noise Characteristics of Several Bionic Airfoils

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Abstract: Based on airfoil theory, cross-sectional configurations were extracted from the wings of four bird species at the 40% spanwise position to reconstruct bionic airfoils. The flow fields and corresponding sound fields over these designed bionic airfoils were simulated numerically using large-eddy simulation (LES) coupled with the Ffowcs-Williams and Hawkings (FW-H) acoustic analogy equation. Unsteady flow simulation results indicated that airflow separation initiated at the leading edge of the suction side under adverse pressure gradient effects. Distinct vortex structures formed downstream of the blade and broke down after shedding from the trailing edge. Among the four bionic airfoils, the seagull airfoil exhibited the highest lift-to-drag ratio, while the owl airfoil showed the lowest; however, the latter possessed excellent noise reduction characteristics. The directional distribution of sound pressure level revealed dipole-source characteristics for the bionic airfoil noise sources.

Key words: Bionic Airfoil; Large Eddy Simulation; Aerodynamic Noise; Lift-to-Drag Ratio

Birds exhibit both gliding flight and silent flight capabilities due to the special morphological structures of their wings, demonstrating that bionic designs based on avian wings hold potential for energy savings and noise reduction. Kondo et al. [1] simulated extracted owl wing sections and found that the owl airfoil’ s lift-to-drag ratio improved compared to the NACA0012 airfoil at low Reynolds numbers. Klän et al. [2] analyzed the structure of barn owl wings, concluding that flow separation on the suction surface of bionic owl airfoils primarily depends on Reynolds number and angle of attack. Lilley et al. [3] identified leading-edge serrations and trailing-edge fringe structures as the main noise reduction elements enabling silent flight in owls. Ge et al. [4] conducted numerical simulations of two-dimensional bionic airfoils, with resulting acoustic fields demonstrating dipole characteristics for bionic airfoil noise sources and thereby revealing the noise mechanism. Ren et al. [5] investigated the effect of the non-smooth leading-edge morphology of long-eared owl wings on noise, finding that the non-smooth model reduced aerodynamic noise by 5–10 dB.

This study extracts airfoil sections from four bird wings at the 40% spanwise position and performs three-dimensional unsteady flow field simulations using large-eddy simulation. The acoustic field distribution is calculated via the FW-H equation based on Lighthill’ s acoustic analogy. Comparative analysis of the aerodynamic and noise characteristics of different bionic airfoils provides valuable insights for the design of micro flapping-wing aerial vehicles and novel airfoil configurations.

1. Extraction of Four Bionic Airfoils

Liu et al. [6] extracted wing information from four bird species using 3D non-contact laser scanning technology and reconstructed the bionic airfoils through fitting methods. The upper and lower surfaces of the bionic airfoils were obtained by adding and subtracting the mean camber line distribution and thickness distribution, respectively, both of which were derived using the Birnbaum-Glauert function equation. [Figure 1: see original paper] shows the airfoils at the 40% spanwise position for the four bird species. This particular cross-section exhibits significant thickness variation and distinct contours, primarily serving to support lift generation while experiencing substantial airflow impact, making it the key region influencing wing aerodynamic performance and thus selected as the focus of this study.

2.1 Computational Grid and Boundary Conditions

Based on the typical dimensions of the four bird wings, the chord length c was set to 0.13 m. [Figure 2: see original paper] illustrates the computational domain geometry, with a spanwise width of 0.2 times the airfoil chord length and translational periodic boundary conditions on both sides. The inlet flow velocity was 10 m/s at 0° angle of attack, the outlet pressure was 1.013$\times10^{5}$ Pa, and the bionic model walls employed no-slip boundary conditions. The Reynolds number based on chord length was 9.0$\times10^{4}$.

The external flow field grid employed a C-type structured mesh [7] with 1.2 million cells, while the spanwise grid used an H-type topology to ensure near-wall surface mesh orthogonality. [Figure 3: see original paper] shows the mesh distribution for the seagull airfoil. The region near the bionic airfoil wall was refined, with the first layer normal to the airfoil surface maintaining $y^{+} < 1$. To verify computational validity, a grid independence study was conducted using the seagull airfoil as an example.

2.2 Numerical Methods

The Spalart-Allmaras (S-A) model was selected as the turbulence model for steady-state calculations, with results serving as initial values for unsteady computations. Unsteady calculations were performed using large-eddy simulation based on the subgrid-scale model [9]. The numerical method employed the SIMPLE algorithm based on the finite volume method, with second-order upwind discretization schemes for all terms [10]. The computational time step satisfied the CFL condition [11]. After the unsteady calculations reached stability, results were input into the FW-H equation for acoustic field computation, with the wall surface selected as the sole noise source.

3.1 Lift and Drag Coefficients

presents the lift and drag coefficients and lift-to-drag ratios for the four bionic airfoils. The results show that the seagull and merganser airfoils exhibit significantly higher lift coefficients than the other two airfoils, both exceeding 0.9. This is attributed to their more curved lower surfaces and greater chordwise thickness, which produce larger pressure differences between upper and lower surfaces. All four bionic airfoils demonstrate lift-to-drag ratios greater than 10, further confirming the high lift-to-drag characteristics of bird wings.

3.2 Wall Pressure Distribution

[Figure 4: see original paper] shows the wall pressure coefficient distributions. All four airfoils exhibit peak pressure coefficients at the leading edge of the suction surface due to the substantial thickness and airflow impact at the leading edge. The seagull and merganser airfoils show relatively high pressure coefficients on the pressure surface, with mean values exceeding 0.3. The teal and merganser airfoils display relatively uniform pressure coefficient distributions along the chord on the pressure surface, indicating uniform pressure distribution resulting from smaller curvature. The seagull airfoil forms a local suction peak at approximately 0.03 m, after which the pressure coefficient stabilizes. The teal airfoil, with its gently curved upper and lower surfaces, exhibits stable pressure coefficient distribution with only a large peak at the leading edge. The merganser airfoil experiences pressure 突变 at both the leading and trailing edges, with a stable region in between. The owl airfoil shows noticeable curvature at 0.03 m and 0.07 m on the pressure surface, producing local pressure double peaks at these locations.

3.3 Velocity Distribution

To further analyze the aerodynamic performance of the bionic airfoils, [Figure 5: see original paper] presents instantaneous velocity contours and streamlines at the mid-span cross-section under 0° angle of attack, revealing flow separation locations. In Figure 5: see original paper, flow separation occurs primarily at 20% chord length on the pressure surface and 80% chord length on the suction surface for the seagull airfoil. Severe flow separation at the trailing edge of the seagull airfoil causes separation bubbles to migrate downstream, forming a distinct vortex street in the downstream region. Both seagull and owl airfoils exhibit flow separation at the leading edge of the pressure surface due to high curvature on the lower surface, generating local vortices in concave regions as airflow passes over the wall. The teal and owl airfoils feature gentle trailing edge distributions with small curvature, making it difficult for airflow to remain attached to the wall and thereby reducing boundary layer bubble separation.

3.4 Pressure and Vortex Distribution

The widely used Q-criterion [12] was employed to analyze vortex motion on suction and pressure surfaces for comparing how unsteady flow fields around airfoils affect sound pressure levels. As shown in [Figure 6: see original paper], the isosurfaces in gray represent vortex structures. Under adverse pressure gradient effects, airflow over the seagull, teal, and merganser airfoils separates at the leading edge of the suction surface, generating distinct vortex structures downstream that break down into small-scale turbulence after shedding from the trailing edge. The owl airfoil exhibits smaller vortex structures at the trailing edge with less pronounced flow separation. Combined with vortex structures at the suction surface trailing edge, this indicates that aerodynamic noise is primarily caused by trailing vortices, demonstrating that trailing-edge scattered noise constitutes the dominant noise source.

3.5 Directional Distribution of Sound Pressure Level

To accurately obtain noise propagation directionality, 12 sound pressure signal receivers were arranged uniformly along a circumference at 15 chord lengths from the bionic airfoils. [Figure 7: see original paper] shows the resulting directional distribution of overall A-weighted sound pressure level. The results indicate that SPL varies significantly with direction, with highest peaks appearing on the upper and lower sides and lowest peaks on the front and back sides, revealing that the primary noise radiation zones are on the upper and lower sides. The directional SPL distributions for all four bionic models exhibit axisymmetry in both horizontal and vertical directions, indicating that the aerodynamic noise source behaves as a dipole source. The merganser airfoil shows a noise peak of 57.64 dB, while the owl airfoil produces the minimum noise with a peak of only 25.20 dB, consistent with its biological function of silent flight.

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Note: Figure translations are in progress. See original paper for figures.