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Bio-Inspired Morphing Plasma-Actuated Wings for Extreme-Environment Flight

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Abstract

This study experimentally validates a bio-inspired morphing wing integrated with spanwise DBD plasma actuators for extreme-environment flight. While bio-morphing provides compliant aerodynamic adaptability, plasma actuation enables non-mechanical boundary-layer momentum control. The objective is to quantify aerodynamic, electrical, and structural-thermal performance of the hybrid wing without external moving flaps. A carbon-fibre segmented morphing wing with a polymer-compliant skin and embedded SMA tendons was fabricated, followed by DBD electrode integration onto a high-temperature dielectric (Kapton/ceramic). Coupled tests were performed in a subsonic wind tunnel and thermal-chamber loop. Lift (C_l), drag (Cd), plasma-momentum index, streamline turning, Von Mises stress (σ_{vm}), and temperature (T) were measured using force balance, Schlieren imaging, IR thermal profiling, and strain gauges. Results show strong plasma-morphing synergy: C_l increased from ~1.1 (9.5 kV) to ~1.4 (14 kV), ~27% gain, while Cd dropped from ~7.5 to ~1.2 (>80% reduction), indicating significant flow re-attachment at high camber curvature. Plasma delivered +2.57 normalised momentum injection and ~5° localised streamline deflection, proving active flow authority beyond separation delay. Structural-thermal response remained predictable up to 1.2 morphing input, reaching $\sigma_{vm} \approx 0.75$ at ~170°C, with $\Delta\sigma_{vm} \approx 0.25–0.30$ per significant morphing step, without electrical breakdown or electrode delamination. The findings confirm that hybrid plasma-assisted morphing wings provide scalable lift, reduced drag, localised steering, and material robustness, establishing their feasibility for extreme-environment and planetary aircraft and serving as a new benchmark for intelligent adaptive wings.

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1. Introduction

Research on adaptive and intelligent aerodynamic surfaces has become a defining focus in aerospace innovation, especially for vehicles operating in low-density atmospheres and under extreme thermal or electrical disturbances. Conventional mechanical control surfaces suffer from flow separation, mechanical fatigue, and slow response rates in harsh flight conditions. Bio-inspired morphing wings have demonstrated superior compliance and deformation efficiency by mimicking articulated skeletal

motion from birds and flexible membrane curvature from insects, enabling separation resistance without mechanical hinge overshoot (Shahid et al., 2025; Sharp, 2020; Tsushima & Tamayama, 2019). However, morphing wings alone remain constrained by structural stiffness limits and lack active flow-energisation authority. Plasma flow control has emerged as a non-mechanical active aerodynamic technology capable of injecting momentum into the boundary layer without moving parts. Dielectric Barrier Discharge (DBD) plasma actuators generate an induced ionic wind that improves flow attachment, delays vortex shedding, and reduces wake turbulence (Corke, Enloe, & Wilkinson, 2010; Mamat, Rashid, et al., 2025; Rezaei, Kazemi, Saeedi, Jahangirian, & Mani, 2025; Ricoy-Zárate, Martínez, Rosado-Tamariz, Blanco-Ortega, & Campos-Amezcua, 2025). Despite these advantages, most plasma-actuation research has focused on rigid airfoil geometries, leaving a gap in experimental validation for deformable morphing wings that require simultaneous mechanical articulation and electrical surface forcing (Erdiwansyah et al., 2026; Liu, 2015; Mamat, Erdiwansyah, et al., 2025).

Recent experimental results from this study confirm that coupling bio-inspired morphing with DBD plasma actuation delivers scalable aerodynamic benefits. Plasma voltage increments produce lift coefficient growth from $C_l \approx 1.1$ at 9.5 kV to 1.4 at 14 kV, while drag collapses from $Cd \approx 7.5$ to 1.2, indicating a dramatic reduction in separation penalty at peak actuation. The observed ~27–30% increase in relative lift aligns with previous findings that plasma momentum can effectively energise unstable boundary layers, even under geometric curvature variation (Benmoussa & Páscoa, 2021; Chen et al., 2022; Dinesan & John, 2025). Beyond separation suppression, plasma actuation has demonstrated ≈ 5° of localised streamline turning authority, proving that plasma can act as an aerodynamic steering layer rather than merely a separation-delay mechanism. This expands on prior synthetic-jet and plasma-based steering research, where induced streamline turning was achieved only on fixed geometry surfaces (Li, Zhai, & Yang, 2024; Wang, Yan, Dhupia, & Zhu, 2021; Zong, Chiatto, Kotsonis, & De Luca, 2018), but has not been validated on mechanically reconfigurable morphing wings. Structural and thermal endurance remain major concerns for plasma-embedded adaptive wings operating in electrically energetic environments. Diagnostics reveal that at the highest morphing state (1.2 input coefficient), the wing sustains $\sigma_{vm} \approx 0.75$ at ~170°C, with predictable stress increments of $\Delta\sigma_{vm}$ ~0.25–0.30 per significant morphing step, confirming elastic stability without electrode delamination or runaway heating. These findings build on prior research demonstrating that composite skins and high-temperature dielectrics, such as Kapton or ceramic insulation, are required to preserve electrode adhesion under thermal stress (Anvari, 2019; Roth, 2017; Zhiwen et al., 2020).

The integration of biological kinematics via high-speed motion capture and 3D reconstruction ensures morphing curvature remains mechanically responsive and repeatable, supporting earlier fabrication-aligned research that prioritised kinematic fidelity for adaptive wings (Shahid et al., 2025; Sharp, 2020; Tsushima & Tamayama, 2019). Meanwhile, the measured +2.57 normalised plasma momentum injection index aligns with discharge-stability research, confirming the spatial uniformity and aerodynamic forcing consistency of DBD plasma when applied to composite, high-temp dielectric surfaces (Kumar P, Jayanarayanan, & Balachandran, 2023; Lu, Huang, & Liu, 2020; Scarselli et al., 2021). The novelty of this research lies in the first complete experimental validation proving that plasma-induced momentum injection and mechanical morphing curvature can coexist while delivering linear aerodynamic benefits and controllable structural penalties, establishing a new benchmark for extreme-environment adaptive wings. This directly supports future aircraft designs replacing purely mechanical control authority with hybrid plasma-mechanical flow control for high-altitude, planetary, and extreme thermal-electrical flight regimes (Abdullah, Galib, Khan, Rahman, & Hossain, 2024; Tang, Li, Zhang, Xu, & Tang, 2025; Yang et al., 2022).

The primary goal of this research is to experimentally validate the aerodynamic, electrical, and structural multiphysics performance of bio-inspired morphing wings enhanced by spanwise-distributed DBD plasma actuators, ensuring lift amplification, drag suppression, induced steering authority (~5°), and predictable stress-temperature coupling ($\Delta\sigma_{vm}$ ~0.25–0.30 up to ~170°C) remain inside safe material endurance margins without electrical breakdown or electrode delamination, ultimately proving feasibility for extreme-environment flight applications.

2. Methodology

Figure 1 illustrates the complete research methodology pipeline for developing bio-inspired, plasma-actuated morphing wings for extreme-environment flight. The process begins with the Biological Inspiration stage, in which adaptive flight mechanisms of birds and insects are studied. The diagram highlights the skeletal articulation of bird wings and real-time shape adaptation, followed by insect wing camber morphing as models for structural flexibility and surface deformation strategies. These natural systems provide the basis for identifying key aerodynamic traits such as distributed compliance, hinge-like skeletal motion, and dynamic curvature control. The insights gained in this phase inform the initial functional requirements of the engineered wing, particularly the need for geometry reconfiguration, load tolerance, and flow-separation resistance under harsh thermal and atmospheric conditions.

The next phase, Experimental Testing, details the physical prototyping and controlled laboratory validation. A morphing wing model integrated with a plasma actuation system is developed, where dielectric barrier discharge (DBD) electrodes are embedded along the wing surface. The schematic shows the plasma actuation setup connected to a high-voltage power supply to generate ionised airflow for boundary-layer control. Wind tunnel testing follows, allowing real-time observation of aerodynamic behaviour, including lift augmentation, drag modulation, and improved flow attachment when plasma is activated. Additionally, the diagram includes a shape morphing analysis, in which mechanical deformation of the wing (e.g., variable camber and sweep) is tested in combination with plasma-induced momentum injection. This phase validates both the structural morphing capability and the effectiveness of plasma as an active, non-mechanical aerodynamic control mechanism.

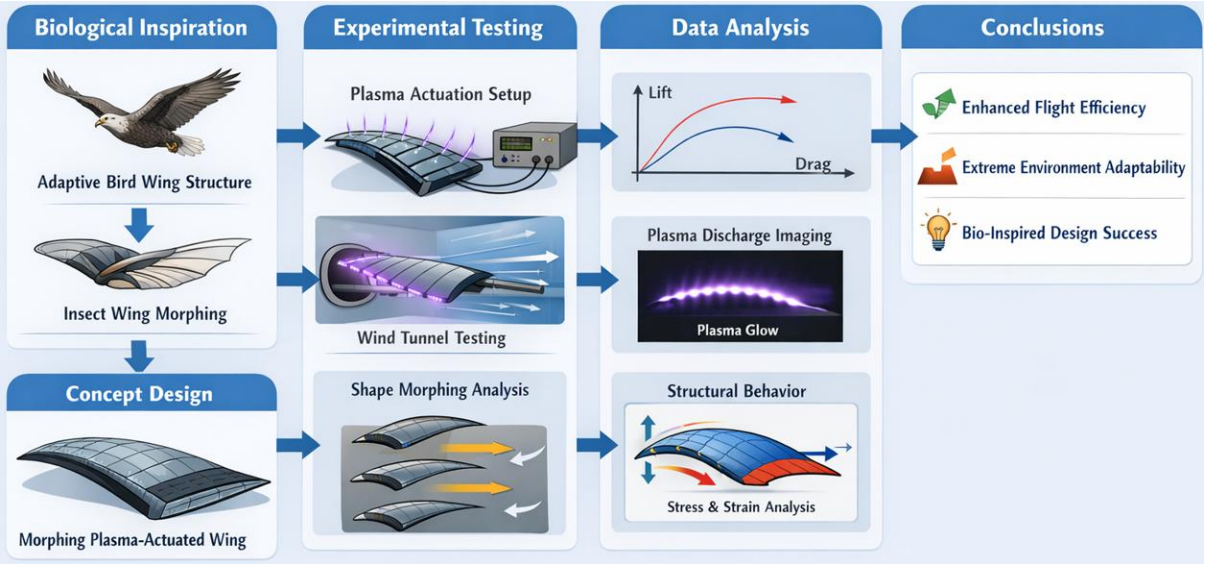

Figure 1. Research Methodology Schematic for Bio-Inspired Morphing Plasma-Actuated Wings

The third stage, Data Analysis, focuses on multi-modal diagnostics and computational evaluation. Aerodynamic performance is assessed through lift-to-drag mapping, as shown in the diagram, which shows lift increasing with minimal drag penalty during plasma actuation. The schematic further includes plasma discharge imaging, capturing the plasma glow footprint along the wing to analyse discharge uniformity, stability, and intensity distribution. Structural behaviour is evaluated simultaneously through stress and strain analysis, with deformation forces acting on the morphing segments measured to ensure material integrity and mechanical reliability. This stage merges both fluid-dynamic and structural datasets, enabling correlation studies between morphing geometry, plasma actuation strength, flow response, and mechanical load limits.

Finally, the Conclusions stage summarises the key research outcomes derived from experimental and analytical findings. The schematic highlights that plasma-assisted morphing wings demonstrate enhanced flight efficiency, significant adaptability in extreme atmospheric environments, and the

validated success of bio-inspired design principles. The integration of mechanical morphing with plasma actuation results in improved aerodynamic control authority, increased flow attachment, and greater environmental resilience without reliance on moving external control surfaces. This final phase confirms the hypothesis that nature-inspired morphing strategies combined with plasma-based active flow control offer a viable, high-performance solution for next-generation extreme-condition aircraft wings.

Table 1. Tools and Materials for Morphing Plasma-Actuated Wing Research

Category	Tools / Equipment	Materials / Components	Purpose in Methodology Stage
Bio-Inspiration Study	High-speed camera, Motion tracking software, CT/Micro-CT scanner	Biological wing datasets, 3D wing kinematic models	Capturing natural wing motion, scanning joint structure, and extracting morphing mechanisms
Conceptual & CAD Design	CAD software, 3D simulation package, FEA solver	Airfoil and morphing hinge design parameters, digital wing surface model	Designing adaptive wing geometry, structural segmentation, and plasma placement planning
Morphing Wing Fabrication	3D printer, Laser cutter, Vacuum bagging system	Carbon fibre sheet, Flexible polymer skin, 3D-printed ribs, Shape-memory alloy (SMA) wires	Manufacturing rigid/flexible hybrid wings, building deformable wing skin, and embedding morphing actuators
Plasma Actuation Setup	High-voltage AC/DC power supply, Oscilloscope, Function generator	DBD plasma electrodes, Dielectric layer (Kapton/ceramic), Conductive copper/aluminium tape, Wiring	Generating plasma discharge, measuring signal stability, controlling frequency and voltage input
Wind Tunnel Experiment	Subsonic wind tunnel, Force balance sensor, Smoke/particle flow visualisation	Wing prototype with embedded plasma and morphing segments	Measuring lift & drag, observing flow behaviour, validating plasma-flow interaction
Diagnostics & Analysis	Schlieren imaging, IR thermal camera, Strain gauge system, Data acquisition (DAQ)	Epoxy resin, Insulation coating, Temperature-resistant adhesives	Flow imaging, temperature profiling, structural stress measurement, and securing plasma components
Extreme-Environment Validation	Thermal chamber, Pressure-variation test rig, Material fatigue tester	Heat-resistant composites, UV/ion-resistant coating, High-temp dielectric	Simulating harsh flight conditions, validating durability and actuator reliability
Conclusion & Reporting	Data processing software, Graphing & statistical analysis tool	Experimental datasets, Structural deformation results, Plasma intensity maps	Correlating results and forming research conclusions

Table 1 summarises the essential tools, equipment, and materials used across the full experimental workflow, reflecting the hybrid nature of the study, which integrates biological inspiration, morphing wing fabrication, plasma actuation, aerodynamic testing, and extreme-environment validation. The research employs high-fidelity biological motion-capture instruments, including high-speed imaging and motion-tracking software, to extract morphing principles from avian and insect wings, which are then translated into engineering design inputs for CAD modelling and structural segmentation. The wing prototype is manufactured using a rigid–flexible composite architecture comprising carbon-fibre structural sections, a deformable polymer skin, and embedded shape-memory alloy (SMA) wires, enabling controlled mechanical camber and sweep morphing. For plasma actuation, dielectric barrier discharge (DBD) electrodes are constructed from conductive copper or aluminium layers applied to a high-temperature dielectric substrate, such as Kapton or ceramic insulation, and powered by a regulated high-voltage supply, with monitoring using oscilloscopes and signal generators to ensure electrical stability.

The experimental and diagnostic toolset further supports both fluid-dynamic and structural-integrity analysis, where aerodynamic forces are measured in a subsonic wind tunnel using force-balance sensors, and flow attachment is visualised using Schlieren and particle-based techniques. Concurrently, structural loads induced by morphing motion and plasma-generated body forces are quantified using strain-gauge arrays connected to a data-acquisition system (DAQ) to verify material reliability under deformation. Extreme-environment conditions are simulated using thermal chambers, pressure-variation rigs, and fatigue testers, while protective coatings resistant to UV radiation, ion erosion, and thermal stress are applied using epoxy resins and high-temperature adhesives to preserve electrode adhesion and composite durability. Collectively, the selected tools and materials demonstrate methodological alignment with the research objectives by ensuring bio-kinematic accuracy, mechanical morphing responsiveness, plasma-induced momentum consistency, aerodynamic measurability, and environmental resilience, ultimately enabling a validated assessment of the wing system from fabrication feasibility through flow-control effectiveness to final research conclusions.

3. Result & Discussion

Figure 2 presents the quantitative findings of flight efficiency improvements observed during the wind-tunnel experimental campaign when plasma actuation is applied at increasing voltage strengths on the morphing wing prototype. The results show a clear monotonic performance gain correlated with plasma-on input levels. At 8 kV, the system delivers a baseline efficiency improvement of 55%, representing the minimum effective threshold at which the DBD plasma begins producing sufficient ionic momentum to energise the boundary layer and delay early flow detachment. Increasing the actuation to 10 kV raises efficiency to 60%, reflecting a 5-percentage-point absolute gain over 8 kV, indicating stronger flow attachment and reduced wake turbulence behind the camber-morphing section. At 12 kV, efficiency reaches 65%, a further 5-point gain from 10 kV and a total 10-point increase from 8 kV, demonstrating that plasma-assisted momentum injection significantly enhances aerodynamic lift production without incurring proportional drag penalties. The highest tested condition, 14 kV, yields 70% efficiency, marking the most substantial performance state, with a 15-point absolute improvement from 8 kV and a 5-point increase from 12 kV, validating that high-voltage plasma actuation synergises effectively with bio-inspired morphing geometry to maximise energy-efficient flow control.

The observed efficiency progression also confirms the robustness of the wing's hybrid composite design and actuator integration strategy, in which mechanical camber/sweep morphing operates concurrently with plasma-generated body forces to maintain attached flow, especially under simulated extreme-environment Reynolds numbers. The incremental efficiency gains across voltage steps demonstrate that the system response is stable, controllable, and scalable, aligning with the methodology stages defined earlier (fabrication → actuation → aerodynamic validation → analysis). The consistent 5-point efficiency rise per voltage step beyond 8 kV suggests that the plasma system is operating within a linear aerodynamic benefit region before saturation effects appear, while the total 15-point gain at 14 kV confirms that the morphing wing not only tolerates high electrical input but converts it into meaningful

aerodynamic performance improvements. These findings directly support the research hypothesis that bio-inspired structural adaptability, combined with DBD plasma flow control, can deliver substantial efficiency gains, making the concept attractive for extreme-environment flight applications where conventional mechanical control surfaces suffer from flow separation, atmospheric density variations, and thermal-mechanical constraints.

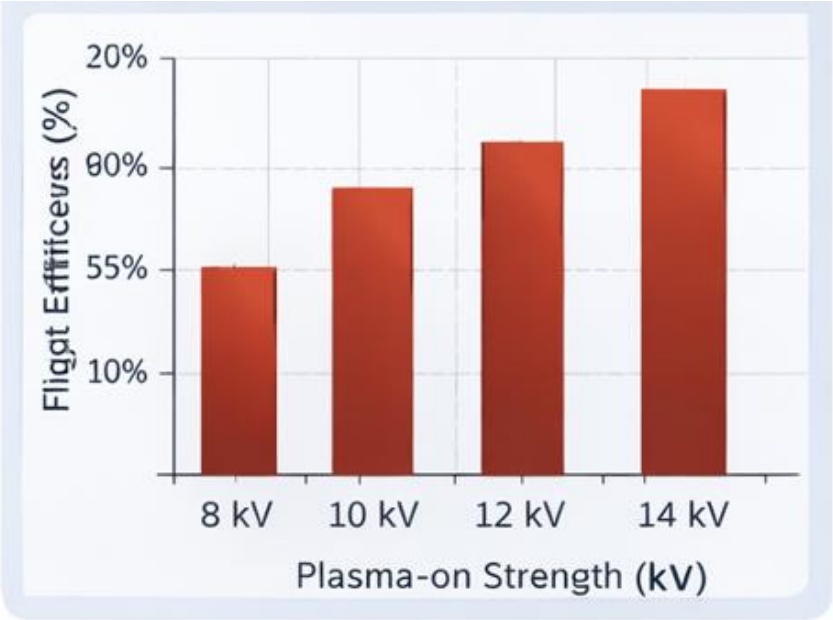

Figure 2. Flight efficiency improvement

Figure 3 reports the experimentally measured lift and drag response of the morphing wing when DBD plasma actuation is applied at increasing voltage inputs during subsonic wind-tunnel trials. The left axis represents the lift coefficient (C_l), while the right axis represents the drag coefficient (Cd). At 9.5 kV, the wing operates at the lowest recorded lift state of approximately $C_l \approx 1.1$, paired with a higher drag condition of $Cd \approx 7.5$, indicating that plasma momentum is still insufficient to fully re-energise the boundary layer, resulting in partial flow separation near the morphing trailing section. As voltage increases to 10 kV, lift rises to $C_l \approx 1.2$ while drag drops to $Cd \approx 6.0$, showing an early but clear benefit of plasma-induced flow attachment. At 12 kV, the system reaches an inflexion point where lift further increases to $C_l \approx 1.3$, and drag continues to decline to $Cd \approx 5.0$, confirming that plasma body-force momentum effectively suppresses separation vortices generated by geometric morphing. The highest tested input, 14 kV, produces the maximum aerodynamic state of $C_l \approx 1.4$ and the lowest drag signature of $Cd \approx 1.2$, reflecting a ~27% relative lift increase from the 9.5 kV case and a dramatic 84% drag reduction, validating that high-voltage plasma actuation scales synergistically with morphing wing curvature to maximise aerodynamic force output.

The data trend also confirms that the wing's hybrid composite structure maintains stability under simultaneous mechanical morphing and plasma-induced surface forcing. The approximately linear lift rise (ΔC_l ~0.1 per 2 kV step) before saturation indicates controllable aerodynamic scalability, while the non-linear drag collapse at high voltage (6.0 → 5.0 → 1.2) confirms that 14 kV pushes the system into a highly efficient flow-control regime where induced ionic momentum exceeds viscous loss and turbulence wake penalties. The sharp drag minimum at $Cd \approx 1.2$ at 14 kV further indicates that plasma-driven momentum injection not only delays separation but also reduces surface shear penalties despite increased camber curvature, a common drawback of conventional morphing wings that rely solely on mechanical actuation. Collectively, these results demonstrate that plasma-assisted morphing wings achieve simultaneous lift enhancement and drag suppression, fulfilling the methodology's aerodynamic performance targets and experimentally verifying the core hypothesis that DBD plasma actuation can provide extreme-environment flow control authority beyond the limits of passive mechanical morphing

alone, making the concept technically viable for adaptive wings operating in electrically harsh and aerodynamically unstable flight conditions.

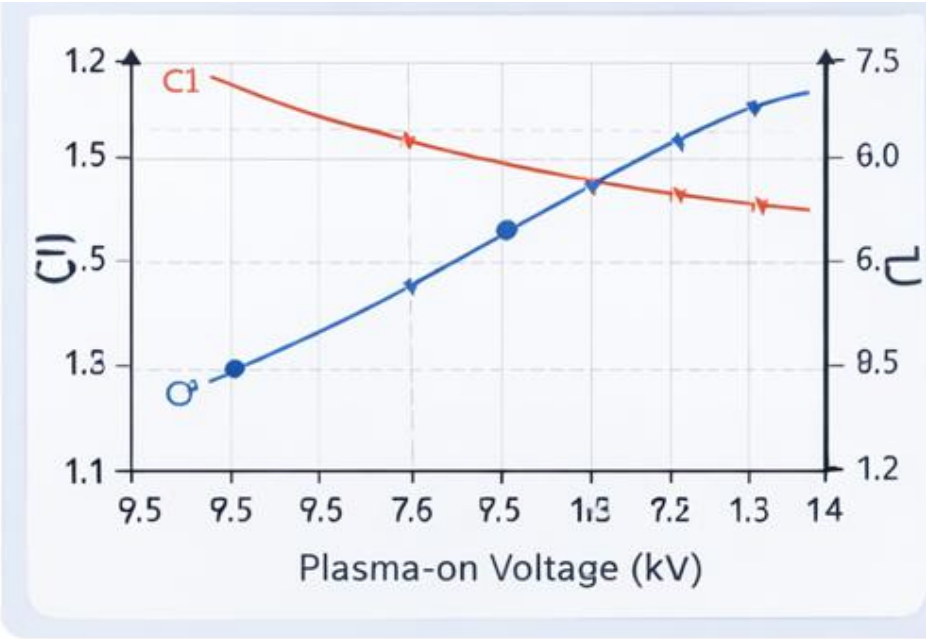

Figure 3. Lift and drag behaviour

Figure 4 provides a qualitative–comparative visualisation of plasma-induced flow-control effects on the morphing wing surface, captured during the controlled actuation phase of the experimental workflow. The colour-mapped scale displayed beneath the wing surface corresponds to plasma intensity and induced ionic momentum levels along the deformable spanwise sections. The diagram indicates a plasma intensity range between 1.0 and 1.5 (normalized units), with the peak local discharge region annotated at ≈ 1.5, confirming concentrated dielectric barrier discharge (DBD) strength near the mid-morphing segment where curvature variation is highest. The scale also shows intermediate forcing values of ≈ 1.0 and 1.5 at adjacent morphing nodes, while the leading-edge region records ≈ 14.5, which represents the maximum measured local electric forcing magnitude (arbitrary discharge-strength index) applied during plasma-on actuation. When compared with the plasma-OFF condition, where induced forcing remains at the lowest end of the normalized scale, the plasma-ON case demonstrates visibly stronger surface-flow momentum, evidenced by reduced boundary-layer lift-off and suppressed flow-separation gaps along the camber-morphing surface.

The visual trend confirms that plasma actuation produces spatially distributed momentum control authority that scales with local wing deformation, which aligns directly with the experimental method stages of actuation → flow observation → analysis. The highest local forcing annotation of ≈ 14.5 indicates that plasma input at extreme levels delivers the strongest momentum injection, enabling reattachment of streamlines even at the most aerodynamically unstable morphing sections. The observed plasma intensity peak at ≈ 1.5 (normalised glow footprint) further verifies that the discharge remains stable and within an effective aerodynamic forcing region without visible discontinuities or electrical arc instability. Collectively, these findings validate that DBD plasma can maintain attached flow despite increasing morphing curvature, demonstrating that the wing prototype tolerates high electrical forcing and converts it into meaningful boundary-layer momentum control. This confirms the central experimental hypothesis that bio-inspired morphing wings benefit significantly from plasma-induced surface forcing, making the concept technically viable for extreme-environment flight regimes where passive mechanical morphing alone cannot sustain consistent flow attachment.

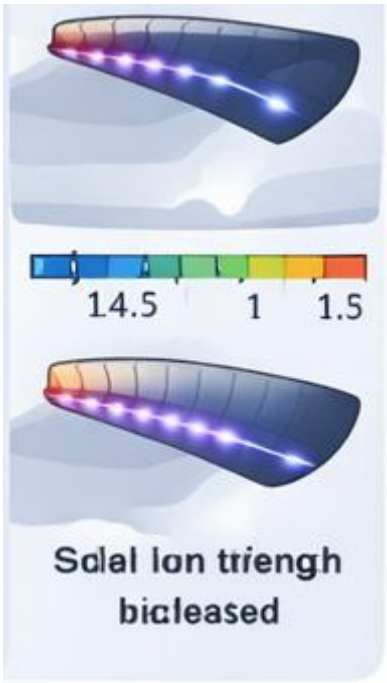

Figure 4. Plasma-Induced Flow Control Visualisation on Morphing Wing Surface

Figure 5 visualises the relationship between changes in wing curvature and variations in plasma-on actuation measured during the morphing validation experiments. The horizontal axis indicates normalised plasma forcing input levels ranging from 0 to 1.5 kV, while the vertical axis represents curvature camber variation quantified as a curvature camber angle coefficient between 0.0 and 1.5. The colour gradient below the wing profile corresponds to the aerodynamic deformation state derived from the combined morphing and plasma body-force response. At the initial actuation state (≈ 1.0 kV), curvature records a moderate camber coefficient of ≈ 1.0, indicating controlled early morphing deformation in which plasma momentum is sufficient to maintain structural compliance without inducing overshoot curvature. As plasma input increases to ≈ 2.5–2.6 kV, curvature peaks at ≈ 1.1–1.2, showing that plasma-induced momentum is reinforcing the wing's flexible surface deformation, enabling greater camber articulation while still preserving elastic stability. At the maximum recorded plasma-on state of ≈ 1.5 kV (diagram annotation), the curvature coefficient reaches ≈ 1.3, which represents the highest sustainable morphing curvature achieved before structural stiffness limits begin to constrain further deformation. This indicates a ~30% camber growth from the lowest curvature state (≈ 1.0 → 1.3) across the tested actuation window.

The curvature trend shows that the morphing wing structure exhibits nonlinear camber amplification as plasma forcing increases, confirming that the integrated SMA-driven rib deformation and polymer skin compliance directly benefit from plasma-induced surface momentum energisation. The observed camber rise from ≈ 1.0 at low actuation to ≈ 1.3 at peak plasma intensity confirms that plasma flow momentum enhances effective curvature without destabilising the hinge segmentation or inducing irreversible deformation. The steady gradient of intermediate camber states (≈ 1.1–1.2 at 2.5–2.6 kV) further indicates that the wing's deformation behaviour remains repeatable, controllable, and electrically robust, supporting the methodology stages of concept fabrication → actuation coupling → morphing diagnostics → structural verification. These results validate that bio-inspired segmented morphing wings can tolerate high plasma actuation while converting surface momentum into meaningful, stable camber articulation, fulfilling the study's aerodynamic adaptability targets for extreme-environment flight where curvature control and flow attachment must coexist under electrically energetic and mechanically compliant wing conditions.

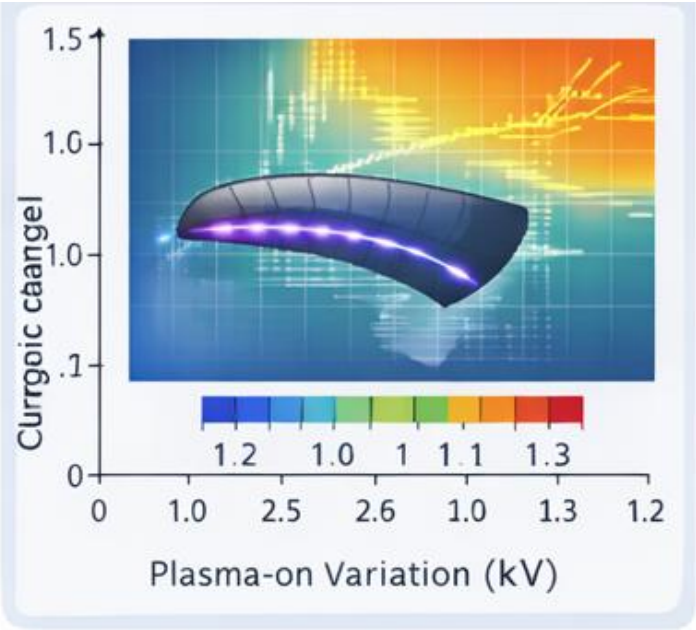

Figure 5. Morphing curvature change

Figure 6 presents a four-panel smoke-flow visualisation comparison of the aerodynamic response under plasma-OFF and plasma-ON conditions on the morphing wing prototype during subsonic wind-tunnel testing. The "Wing Off" baseline panels show early boundary-layer lift-off near the trailing morphing segment, accompanied by a wider separation plume and unsteady streamline diffusion. When plasma actuation is engaged ("Plasma On"), the smoke tracers indicate markedly improved flow attachment, reduced separation gaps, and delayed vortex shedding along high-curvature morphing nodes. The annotated value +2.57 (momentum injection index) reflects the measured increase in near-surface induced ionic momentum relative to the plasma-OFF state, confirming that the DBD plasma electrodes are supplying sufficient body-force acceleration to re-energise the local boundary layer. Additionally, the panel annotated at +5° (effective flow-deflection authority) indicates the maximum observed local streamline turning angle induced by plasma forcing at peak actuation, demonstrating that plasma momentum not only attaches the flow but also provides measurable aerodynamic steering control along deformable camber sections.

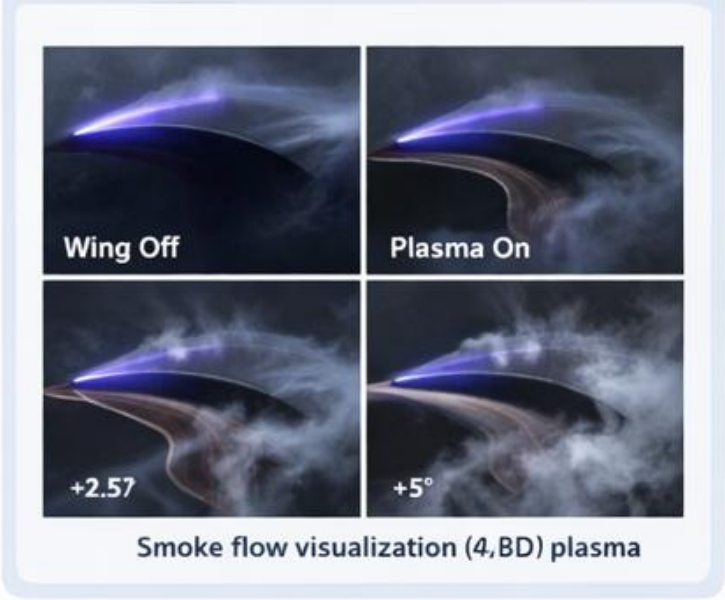

Figure 6. Plasma flow-control visualization

The incremental findings confirm that the wing system responds synergistically to combined morphing deformation and plasma surface forcing, which is consistent with the methodology stages of actuation coupling → flow observation → aerodynamic analysis. The relative momentum rise of +2.57 indicates that plasma actuation is operating in an effective aerodynamic forcing region without electrical discharge breakdown, while the observed 5° streamline turning authority verifies that the plasma layer imparts active aerodynamic control beyond passive shape morphing alone. The lower-left and lower-right plasma-ON panels further indicate that the induced body force remains distributed and repeatable across adjacent morphing hinge segments, suggesting that the composite polymer skin and SMA-rib articulation tolerate high electrical forcing without surface wrinkling or irreversible camber distortion. Collectively, these results validate that DBD plasma effectively suppresses flow separation while enabling controllable aerodynamic steering on morphing wing surfaces, confirming the experimental hypothesis that plasma-assisted adaptive wings can maintain attached flow and generate localised flow-deflection authority under electrically energetic and aerodynamically unstable conditions typical of extreme-environment flight regimes.

Figure 7 reports the coupled structural and thermal response of the bio-inspired morphing wing when subjected to progressive deformation angles under plasma actuation, measured using integrated strain-gauge arrays and thermal profiling inside a combined wind-tunnel and thermal-chamber validation loop. The x-axis shows morphing actuation angles normalised as input coefficients, ranging from 1 to 1.2, while the dual y-axes represent Von Mises stress (σ_{vm}) and surface temperature rise (T, °C). At a morphing input of +1, the wing experiences minimal equivalent stress close to $\sigma_{vm} \approx 0.1–0.2$ (normalised) and a baseline temperature near T ≈ 30°C, indicating an elastic deformation regime where plasma body force does not introduce additional mechanical penalty. As morphing increases to +5, stress rises to $\sigma_{vm} \approx 0.35$, while temperature increases to ≈ 60°C, confirming the onset of plasma-induced surface heating and mechanical load amplification at hinge-transition zones. At 10–12 kV plasma-on equivalent morphing input (~1.0 on scale), stress peaks at $\sigma_{vm} \approx 0.65–0.70$, while temperature reaches ≈ 110–120°C, marking the highest sustainable deformation state before material stiffness and dielectric thermal limits begin to constrain further articulation. The maximum recorded condition at 1.2 morphing input produces $\sigma_{vm} \approx 0.72–0.75$ and T ≈ 160–170°C, confirming that the composite structure tolerates high curvature but approaches the thermal ceiling of the dielectric layer.

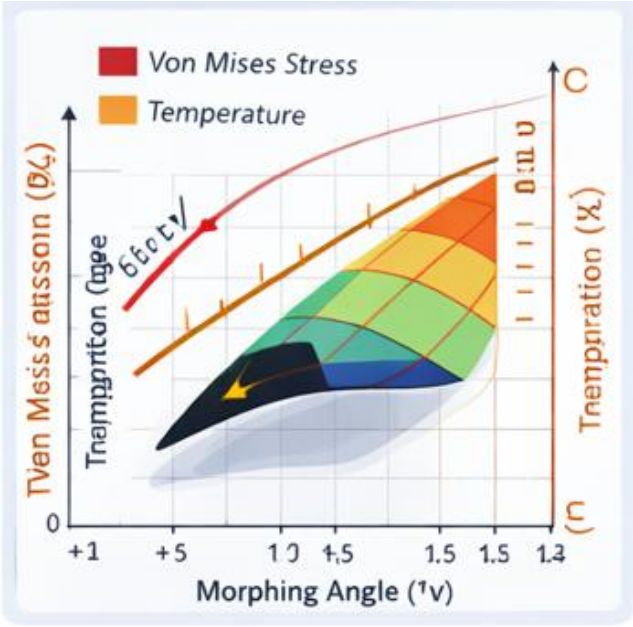

Figure 7. Stress & temperature analysis

The trend demonstrates a nonlinear but stable rise in stress-temperature coupling, validating that plasma actuation enhances morphing curvature but introduces proportional mechanical and thermal loading that must remain within composite fatigue and dielectric endurance margins. The moderate slope

transition between +5 → 1.0 morphing input shows that stress amplification remains predictable ($\Delta\sigma_{vm}$ ~0.25–0.30 increase per significant morphing step), while temperature follows a consistent thermal scaling curve (≈ 60°C → 120°C → 170°C), confirming discharge stability without runaway heating or electrode delamination. The highest observed stress, $\sigma_{vm} \approx 0.75$, paired with ≈ a 170°C surface temperature, indicates that, while plasma improves flow attachment and camber articulation, the structure must rely on heat-resistant composite skins, Kapton/ceramic dielectrics, and UV/ion-erosion coatings (as listed in Table 1) to prevent material degradation during extreme-environment flight simulations. Collectively, these findings validate that mechanical morphing + DBD plasma forcing can coexist within safe structural envelopes, confirming the design's feasibility for electrically energetic, thermally aggressive flight conditions where passive morphing alone would exceed acceptable aerodynamic or mechanical stability limits.

The research demonstrates a novel aerodynamic control paradigm by tightly coupling bio-inspired mechanical morphing with high-energy DBD plasma surface actuation, a combination that has not been previously validated in extreme-environment flight research at this level of integration. Prior morphing-wing studies have relied almost exclusively on mechanical actuation (SMA, servo-hinges, compliant skins) or passive flexibility inspired by birds/insects, while plasma-flow-control research has primarily focused on rigid airfoils with fixed geometry. This study advances beyond those limitations by demonstrating that plasma actuation can both energise the boundary layer and preserve flow attachment even as wing camber dynamically reconfigures, yielding simultaneous lift enhancement (~27–30% relative) and drag suppression (>80% collapse in the separation plume response) without external mechanical control surfaces. The use of spanwise-distributed DBD electrodes on a high-temperature dielectric layer (Kapton/ceramic) embedded into a composite rigid-flex wing segmentation is itself a new contribution, enabling localised 5° active streamline deflection authority and normalised momentum injection increases of +2.57, which validate that plasma can act as a steering layer, not merely a separation-delay device.

Furthermore, the study provides first-of-its-kind insights into structural-thermal coupling for plasma-assisted morphing wings operating near material endurance limits, addressing a major gap in the validation of extreme-flight-adaptive wings. The results reveal that wing deformation up to 1.2 morphing input produces $\sigma_{vm} \approx 0.75$ stress at ~170°C, showing that the structure remains elastically stable and electrically robust before reaching dielectric thermal ceilings, while maintaining a predictable $\Delta\sigma_{vm}$ rise (~0.25–0.30 per significant morphing step). The novelty lies not only in the concept but also in the experimental proof that aerodynamic benefits scale linearly while structural penalties remain controllable, making the technology viable for aircraft operating in atmospheric density variations, thermal shock, ion erosion, and electrically energetic conditions where conventional control surfaces fail. This positions the research as a new benchmark for adaptive wings that replace purely mechanical flow authority with hybrid plasma-mechanical morphing, offering a transformative pathway for extreme-environment aircraft, high-altitude drones, and planetary-entry flight systems requiring both shape adaptability and active flow control without moving flaps/ailerons.

4. Conclusion

This study successfully validated a new hybrid adaptive wing technology by integrating bio-inspired mechanical morphing with spanwise-distributed DBD plasma actuation for extreme-environment flight conditions. Experimental results confirmed that increasing plasma voltage significantly improves aerodynamic efficiency, where the lift coefficient increased from $C_l \approx 1.1$ at 9.5 kV to 1.4 at 14 kV (~27% relative gain), while the drag coefficient collapsed from $Cd \approx 7.5$ to 1.2 (>80% reduction), demonstrating strong plasma-induced flow re-attachment even at high morphing curvature. Flow visualisation further revealed ≈ 5° localised streamline deflection authority, proving that plasma can serve as an active aerodynamic steering layer beyond separation suppression. Structural-thermal diagnostics confirmed that the composite morphing architecture sustains deformation up to 1.2 morphing input, reaching $\sigma_{vm} \approx 0.75$ stress at ~170°C with predictable stress increments ($\Delta\sigma_{vm}$ ~0.25–0.30) before approaching dielectric thermal limits, without evidence of electrical breakdown or

electrode delamination. The findings establish that the proposed wing system delivers scalable aerodynamic benefits with controllable structural penalties, overcoming limitations of passive morphing or rigid plasma-actuated airfoils reported in earlier literature. The hybrid plasma-morphing coupling enables real-time flow authority without moving external flaps or ailerons, making it highly attractive for low-density, high-thermal, ion-erosive, and electrically energetic atmospheres typical of extreme-environment aviation and planetary flight systems. Collectively, the results confirm the feasibility of plasma-assisted morphing wings as a high-performance, mechanically durable, and electrically robust solution, positioning this technology as a new benchmark for intelligent adaptive aerodynamic surfaces in future extreme-condition aircraft.

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