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Aerodynamic Proof-of-Concept for a Dual-Regime Pressurized Morphing Wing Across Subsonic, Transonic, and Supersonic Regimes

Numerical Analysis of Pneumatic Supercritical-to-Biconvex Geometric Transitions for Wave Drag Mitigation and Efficiency Envelope Optimization

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Dataset: 43 Static OpenFOAM CFD Cases | **Operational Envelope:** Mach 0.15 – 2.50

ABSTRACT

Modern high-speed aircraft face a well-known trade-off: subsonic flight requires thick, cambered supercritical airfoils for high lift and delayed shock formation, whereas supersonic flight demands thin, symmetric biconvex profiles to minimize wave drag. Traditional mechanical variable-geometry systems add substantial structural weight, complex linkages, and mechanical failure risks. To resolve this compromise, this study presents a computational fluid dynamics (CFD) proof-of-concept evaluating a dual-regime pneumatic morphing wing operating from Mach 0.15 to Mach 2.5. The hybrid architecture combines an internal rigid, load-bearing biconvex core with a flexible outer elastomeric composite skin. Nitrogen pressurization of internal chambers expands the skin into a rounded supercritical profile optimized for high lift slope and transonic shock delay (Mach 0.15–0.95). Gas evacuation causes the skin to collapse flush against the core, exposing a razor-thin biconvex profile tailored to minimize wave drag in supersonic flight (Mach 1.0–2.5). To evaluate baseline aerodynamic feasibility without dynamic mesh overhead, 43 static rigid-mesh cases were simulated using OpenFOAM (**rhoSimpleFoam** and **rhoCentralFoam**) managed via **SimFlow**. Force and moment evaluations show a peak subsonic efficiency of $(L/D)_{max}$ ≈ 32.9 at Mach 0.4, a controlled transition through the transonic dip (Mach 0.8–1.2), and an efficiency recovery to $(L/D)_{max}$ ≈ 9.3 at Mach 2.5 under the collapsed profile. These numerical results confirm baseline feasibility, establishing the theoretical framework prior to experimental laboratory wind-tunnel testing.

Mach 0.15–2.5	43 CFD Cases	32.9	9.3
FULL FLIGHT ENVELOPE	12 SUBSONIC / 31 HIGH-SPEED	SUBSONIC $(L/D)_{MAX}$ (M=0.40)	SUPERSONIC $(L/D)_{MAX}$ (M=2.50)

1. EXECUTIVE OVERVIEW & CORE ARCHITECTURE

The Hybrid Dual-Regime Pneumatic Morphing Wing is an aerospace structural architecture engineered to achieve optimal lift-to-drag efficiency across an extreme flight envelope spanning takeoff (Mach 0.15) to supersonic cruise (Mach 2.5). Fixed-wing aircraft are permanently locked into a single geometry: either thick, cambered airfoils tailored for low-speed lift or razor-thin symmetric wedges designed for supersonic wave drag reduction. Flying a subsonic profile at Mach 2.0 generates severe detached normal shock drag, whereas operating a thin supersonic wing at landing speeds results in premature flow separation and dangerously high stall speeds.

This architecture resolves that fundamental trade-off by reconfiguring its external contour between two discrete boundary states without mechanical hinges or external surface steps: (1) an **Inflated Supercritical Airfoil State (M < 1.0)** pressurized by internal Nitrogen (N_2) for high L/D ratios and gentle stall behavior; and (2) a **Collapsed Biconvex Airfoil State (1.0 ≤ M ≤ 2.5)** evacuated via vacuum suction so external atmospheric pressure clamps the elastomeric sleeve tightly against an internal load-bearing biconvex core.

2. THE AERODYNAMIC PROBLEM & ARCHITECTURAL TRADE-OFFS

In compressible aerodynamics, flow equations change character from elliptic (subsonic, M < 1.0) to hyperbolic (supersonic, M > 1.0). In subsonic and transonic flight (Mach 0.15–0.95), generating lift without severe boundary-layer separation requires a rounded leading edge and a flattened upper surface that weakens local shock waves **(Anderson, 2016)**. Conversely, past Mach 1.0, a blunt leading edge forces a strong detached bow shock to form, converting energy into massive wave drag. Supersonic efficiency requires an ultra-thin biconvex profile so oblique shock waves attach cleanly to the nose.

2.1 Comparative Architectural Evaluation

Design Criterion	Fixed Supercritical Wing	Fixed Supersonic Wedge	Mechanical Variable-Sweep	Hybrid Pneumatic Wing (This Work)
Subsonic Efficiency (M ≤ 0.4)	High (L/D > 30), gentle stall	Poor (L/D < 8), high stall speed	High when unswept, heavy wing root	Optimal $((L/D)_{max} \approx 32.9$ at M=0.4)
Supersonic Drag (M ≥ 1.5)	Severe detached bow shock drag	Low wave drag, attached shock	Moderate; hinge steps & gaps add drag	Low wave drag $((L/D)_{max} \approx 9.3$ at M=2.5)
Surface Continuity	Continuous rigid skin	Continuous rigid skin	Discontinuous flaps, seals, and joints	100% seamless elastomeric contour
Actuation & Load Synergy	Zero morphing weight penalty	Zero morphing weight penalty	Heavy hydraulics; actuators fight loads	Lightweight hollow core; freestream clamps skin

> **Pneumatic-Elastomeric Synergy:** Mechanical variable-geometry systems suffer from high hydraulic weight, boundary-layer tripping at surface steps, and high actuator power requirements. Decoupling bending loads (carried by the rigid core) from aerodynamic shaping (handled by the elastomeric sleeve) eliminates mechanical linkages while harnessing external freestream pressure to hold the supersonic profile in place.

3. PNEUMATIC MECHANISM & PRESSURE DIFFERENTIAL PHYSICS

To prevent membrane dimpling during subsonic flight and eliminate skin detachment during supersonic expansion, the morphing wing is governed by explicit pressure differential relationships across four variables:

- **Ambient Static Pressure (P_∞):** The atmospheric pressure at flight altitude (e.g., 54.0 kPa at 5,000 m or 12.1 kPa at 15,000 m).
- **External Stagnation Pressure ($P_{surf,max}$):** Peak pressure on the leading edge where flow decelerates to rest.
- **Minimum Surface Pressure ($P_{surf,min}$):** Lowest static pressure on the skin (upper crest in subsonic, expansion fans in supersonic).
- **Internal Chamber Pressure ($P_{internal}$):** Regulated Nitrogen (N_2) pressure or vacuum level inside the wing cavity.

3.1 Pressure Differential Operational Matrix

Flight Regime	Mach (M)	Active Profile	$P_{surf,max}$	$P_{surf,min}$	$P_{internal}$ Set	Governing Condition & Result
Takeoff / Low Cruise	0.15 – 0.40	Supercritical	55 – 61 kPa	40 – 51 kPa	75 – 80 kPa	$P_{internal} > P_{surf,max}$ ($\Delta P \approx +15$ to $+25$ kPa). Hoop tension prevents nose dimpling.
High Subsonic	0.70 – 0.95	Supercritical	75 – 88 kPa	18 – 33 kPa	95 – 110 kPa	$P_{internal} > P_{surf,max}$ ($\Delta P \geq +20$ kPa). Suppresses panel flutter.
Sonic / Supersonic	1.00 – 2.50	Biconvex	41 – 131 kPa	1.9 – 14.2 kPa	≤ 1.0 kPa	$P_{internal} < P_{surf,min}$ ($\Delta P < 0$). Vacuum draws skin flush before shock formation.

4. ELASTOMERIC MATERIALS & AEROTHERMAL LIMITS

Thin-walled pressure vessel calculations (Laplace's Law: $\sigma_h = \Delta P \cdot R / t$) indicate that under peak inflation ($\Delta P \approx 50$ kPa, R = 50 mm, t = 0.5 mm), maximum circumferential hoop stress is 5.0 MPa. In supersonic cruise (Mach 2.5 at 15,000 m), turbulent boundary-layer recovery calculations yield an equilibrium wall temperature of approximately 180°C to 195°C.

Commercial off-the-shelf (COTS) Fluorosilicone (FVMQ) provides a tensile strength of 7–11 MPa (1.4–2.2× safety factor) and a continuous thermal rating of 230°C. Viton fluoroelastomer (FKM) offers 10–20 MPa tensile strength and a 250°C thermal rating. Peak inflation stresses occur only in subsonic flight when skin temperatures are cool, while peak heating occurs at Mach 2.5 when the skin is clamped flat under zero inflation stress. Thus, structural and thermal peak loads are decoupled in time.

5. COMPUTATIONAL METHODOLOGY & OPENFOAM SETUP

Simulating a deforming membrane across subsonic and supersonic regimes using two-way Fluid-Structure Interaction (FSI) introduces mesh distortion risks and high computational costs. To establish baseline aerodynamic proof-of-concept, a quasi-steady discrete boundary-state methodology was implemented. The two extreme equilibrium states—fully inflated supercritical and fully collapsed biconvex—were modeled as rigid domains across a 43-case matrix in OpenFOAM.

Dataset structure and file mapping were organized within the `my_Cases` repository. Low-speed cases (Mach 0.15 and 0.40) utilized nested directory paths with identical parent-child names, high-speed cases past Mach 1.0 utilized nested subdirectories named `new`, and intermediate transonic cases (Mach 0.70 to 0.95) maintained direct root folder organization.

5.1 Dual-Solver Strategy

- `rhoSimpleFoam` **(Cases 1–12, M = 0.15 & 0.40):** Steady-state, pressure-based RANS solver utilizing SIMPLE pressure-velocity coupling. Ideal for low-speed flow where density variations are negligible.
- `rhoCentralFoam` **(Cases 13–43, M = 0.70 to 2.50):** Transient, density-based solver using Kurganov and Tadmor central-upwind flux schemes **(Kurganov & Tadmor, 2000)**. Accurately captures sharp oblique shocks and Prandtl-Meyer expansion fans without numerical oscillations. Turbulence was modeled using the Spalart-Allmaras single-equation model **(Spalart & Allmaras, 1992)**.

6. COMPLETE 43-CASE SIMULATION MATRIX

Mach (M)	Regime	Airfoil State	OpenFOAM Solver	Angle of Attack (α) Schedule	Cases
0.15	Takeoff / Approach	Supercritical	rhoSimpleFoam	-4.0°, 0.0°, 4.0°, 8.0°, 12.0°, 15.0°, 18.0°	7
0.40	Subsonic Cruise	Supercritical	rhoSimpleFoam	-4.0°, 0.0°, 4.0°, 8.0°, 12.0°	5
0.70	High Subsonic	Supercritical	rhoCentralFoam	-2.0°, 0.0°, 2.0°, 4.0°, 6.0°	5
0.80	Transonic Entry	Supercritical	rhoCentralFoam	-2.0°, 0.0°, 2.0°, 4.0°	4
0.85	Transonic Cruise	Supercritical	rhoCentralFoam	-2.0°, 0.0°, 2.0°, 4.0°	4
0.95	Near-Sonic Limit	Supercritical	rhoCentralFoam	-2.0°, 0.0°, 2.0°	3
1.00	Sonic Transition	Collapsed Biconvex	rhoCentralFoam	-2.0°, 0.0°, 2.0°	3
1.20	Low Supersonic	Collapsed Biconvex	rhoCentralFoam	-2.0°, 0.0°, 2.0°	3
1.50	Supersonic Climb	Collapsed Biconvex	rhoCentralFoam	-2.0°, 0.0°, 2.0°	3
2.00	Supersonic Cruise	Collapsed Biconvex	rhoCentralFoam	-2.0°, 0.0°, 2.0°	3
2.50	High Supersonic	Collapsed Biconvex	rhoCentralFoam	-2.0°, 0.0°, 2.0°	3
TOTAL VALIDATED CASES				**28 Supercritical / 15 Biconvex**	**43**

7. AERODYNAMIC RESULTS & PERFORMANCE ANALYSIS

Analysis of calculated force coefficients (C_L, C_D, C_m) confirms that transitioning profile geometry successfully bridges the subsonic and supersonic efficiency gap:

- **Subsonic Peak (M = 0.15–0.40):** The supercritical profile delivers a steep lift curve slope and achieves peak efficiency at $(L/D)_{max} \approx 32.9$ at Mach 0.40 ($\alpha = 4.0°$). The rounded leading edge delays stall up to $\alpha = 15°–18°$.
- **Transonic Transition (M = 0.80–1.20):** Evacuating the wing at Mach 1.0 transitions the surface to the collapsed biconvex core prior to severe shock wave divergence, managing the transonic dip cleanly.
- **Supersonic Recovery (M = 1.50–2.50):** With the skin vacuum-clamped flush against the biconvex core, oblique shocks attach to the leading edge. Wave drag is minimized, restoring efficiency to $(L/D)_{max} \approx 9.3$ at Mach 2.5.

8. PHYSICAL TESTING ROADMAP & EXPERIMENTAL FRAMEWORK

While RANS CFD confirms baseline aerodynamic feasibility, experimental testing is required to characterize membrane dynamics, sealing integrity, and aeroelastic flutter boundaries. A four-phase physical testing roadmap has been structured for institutional implementation:

- **Phase 1: Benchtop Pneumatic Cycling:** 1,000-cycle fatigue test of a 3D-printed SLA core with a cast silicone sleeve, cycling between +50 kPa inflation and -50 kPa vacuum at 0.25 Hz to verify zero pressure decay or skin tearing.
- **Phase 2: Subsonic Wind Tunnel Testing:** Mounting a 3D-printed model on a multi-component strain-gauge balance in a subsonic tunnel (Suez Canal University / Cairo University) at Re $\approx 2\times10^5$ to measure C_L and C_D polars against `rhoSimpleFoam` predictions.
- **Phase 3: Aeroelastic Flutter Boundary:** Boundary-layer tuft visualization and high-speed video monitoring (240 fps) to determine critical flutter differential pressures (ΔP_{crit}) under freestream flow.
- **Phase 4: Supersonic Schlieren Imaging:** Optical Schlieren visualization in a high-speed blowdown facility to confirm attached oblique shock angles (β) at Mach 1.5–2.5 against `rhoCentralFoam` pressure contours.

> **Shoestring Benchtop Demonstration:** For low-cost verification (<500 EGP / ~$10 USD), a 10–12 cm span 3D-printed core wrapped in an elastomeric sleeve can be actuated manually via a 100 mL syringe. This provides a tactile physical model demonstrating positive pressure inflation and vacuum clamping.

9. CONCLUSION

This research demonstrates the aerodynamic proof-of-concept of a dual-regime pneumatic morphing wing across Mach 0.15 to 2.5. By utilizing internal pressure control to alternate between an inflated supercritical profile and a collapsed biconvex profile, the design eliminates the heavy actuators and surface gaps of mechanical variable-geometry systems. The 43-case OpenFOAM CFD matrix confirms high subsonic efficiency ($(L/D)_{max} \approx 32.9$) and effective supersonic wave drag reduction ($(L/D)_{max} \approx 9.3$), establishing a verified theoretical foundation for physical prototype testing.

DECLARATION OF GENERATIVE AI AND AI-ASSISTED TECHNOLOGIES

During the preparation of this work, the author utilized AI-assisted technologies for drafting assistance, structural organization, and language refinement. Following these suggestions, the author thoroughly reviewed, verified, and revised all technical content, calculations, and CFD data, taking full responsibility for the integrity of the published work.

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