Structural design of multi-configuration morphing wing

多维度变形机翼机构-结构设计

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Presentation outline

Part I: Structural design of variable-camber wing for supersonic transport aircraft

面向超音速客机的变弯度前后缘机翼结构设计

Part II: An integrated design framework for planar multi-configuration morphing airfoil

平面多维度变形翼机构/结构一体化设计方法

Background

- The next-generation supersonic transport aircraft faces two challenges: **reducing sonic boom (声爆)** and **improving aerodynamic efficiency (气动效率)**.
- **Morphing wing technologies** such as **variable-camber leading and trailing edges, foldable wingtips**, adapt to different flight conditions by adjusting the wing shape during the flight. They can **reduce noise and improve the aerodynamic performance** of supersonic aircraft.



First-generation SST: Concorde

Sonic boom: **108 dB**

Fuel consumption: **0.1 kg/passenger/km**

Sonic boom

Morphing technology

Aerodynamic efficiency



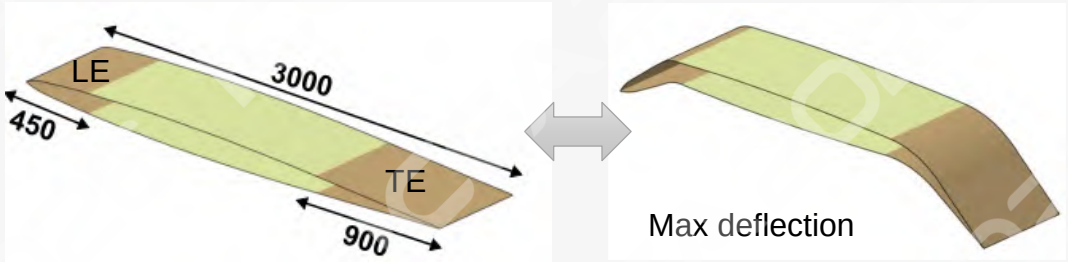
Next-generation SST

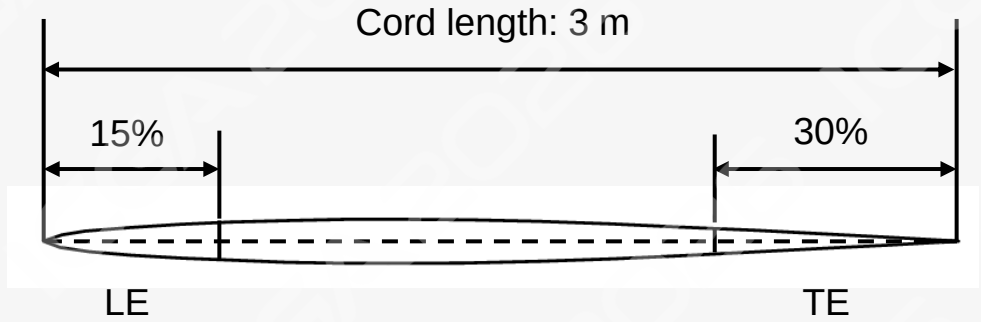
Sonic boom: **65-70 dB**

Fuel consumption: **0.06-0.08 kg/passenger/km**

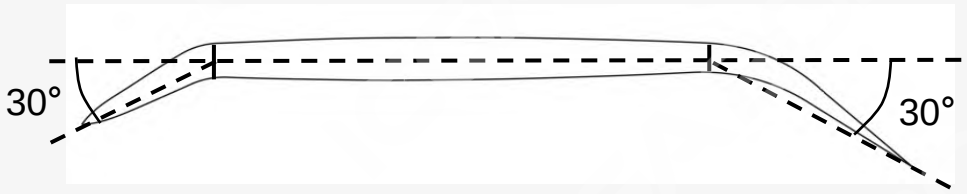
Wing profile and morphing targets

- Wing profile: **NACA-66 airfoil** with **3m** cord length
- Maximum deflection of leading and trailing edges: **30°**
- Design load: **0.01MPa** aerodynamic pressure

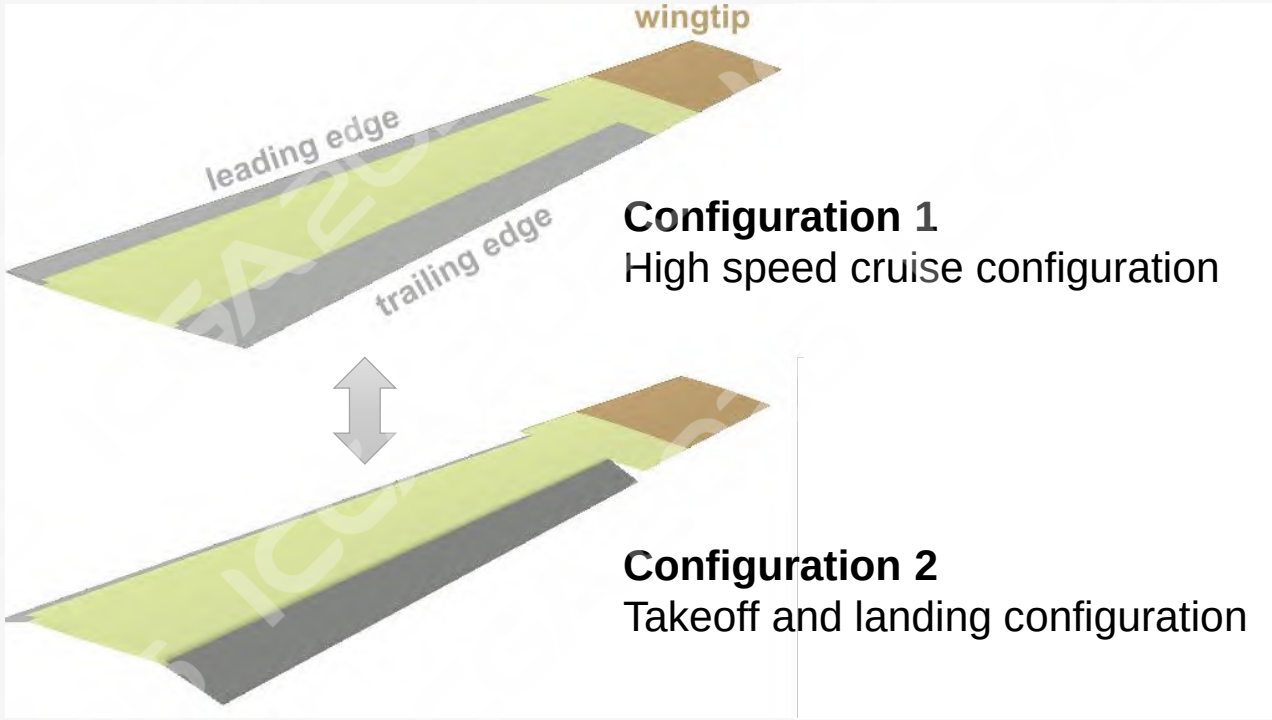




NACA66 thin airfoil



Max deflection

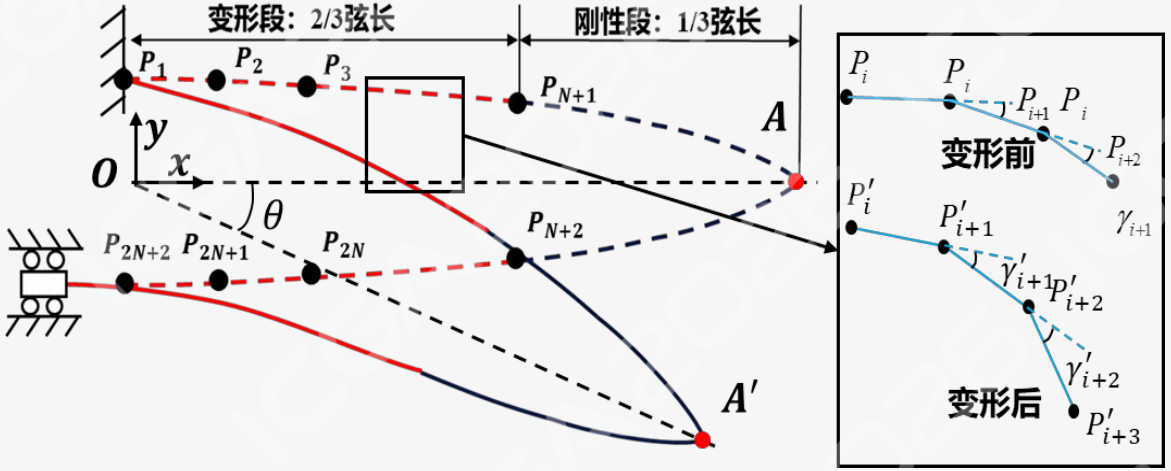


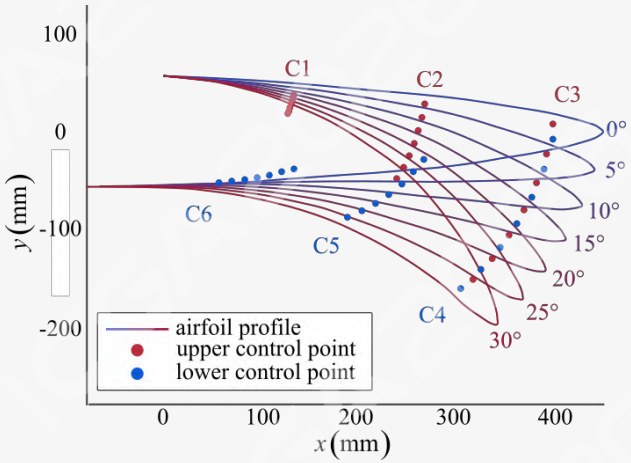
Configuration 1
High speed cruise configuration

Configuration 2
Takeoff and landing configuration

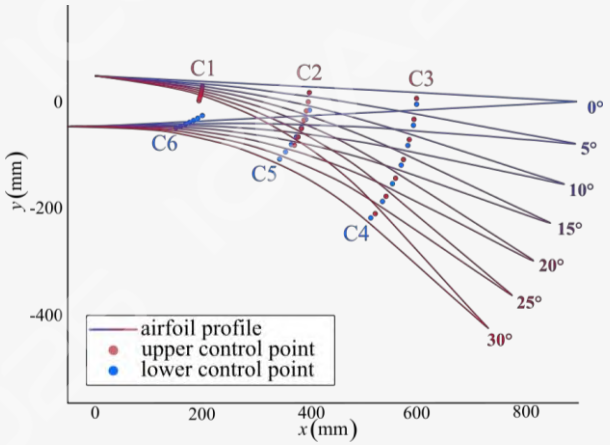
Airfoil deflection profile design

- The leading and trailing edges consist of a deformable section and a rigid section
- The root of the upper skin is fixed, the root of the lower skin can slide
- **Algorithm: let the upper and lower skins undergo uniform bending deformation as much as possible**





LE deflection process



TE deflection process

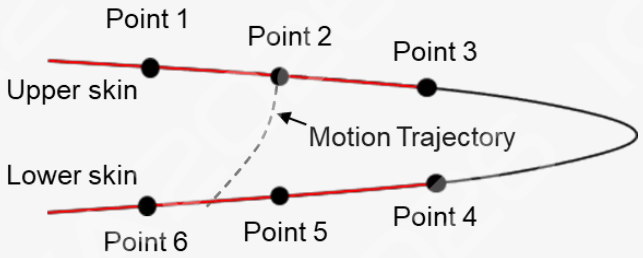
➢ Constraint conditions in the algorithm:

(a) **Constant arc length:** $P_iP_{i+1} = P'_iP'_{i+1}$

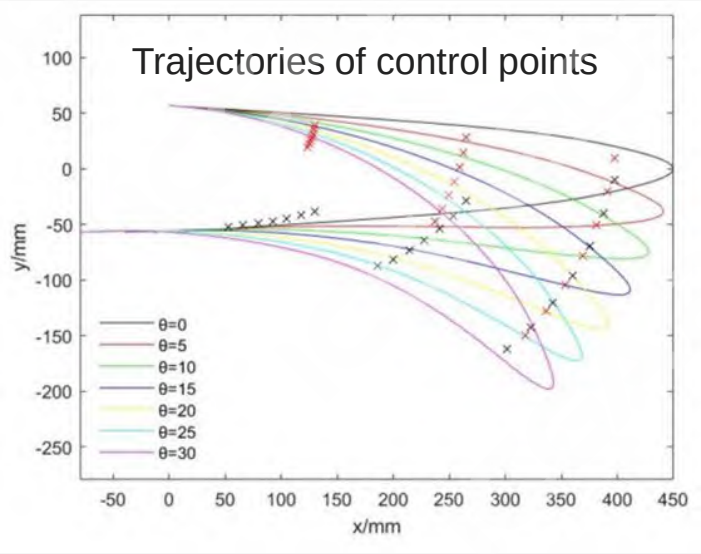
(b) **Constant curvature change:** $\gamma'_i - \gamma_i = \gamma'_{i+1} - \gamma_{i+1}$

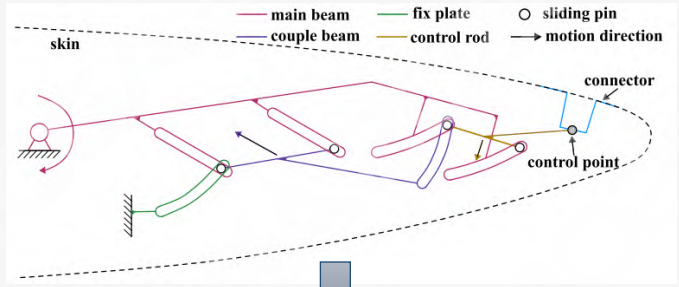
Deformation drive mechanism

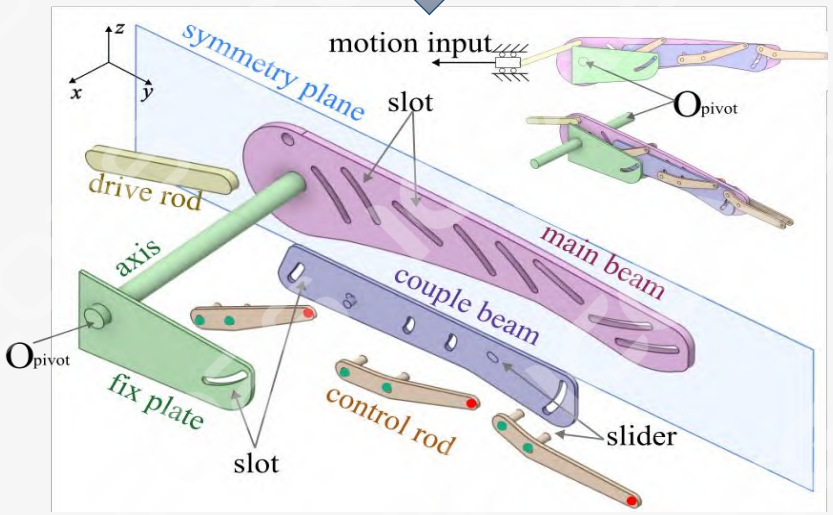
- **Six control points:** three on the upper skin and three on the lower skin
- The trajectories of control points are controlled by a **1-DOF closed-chain sliding-slot mechanism**



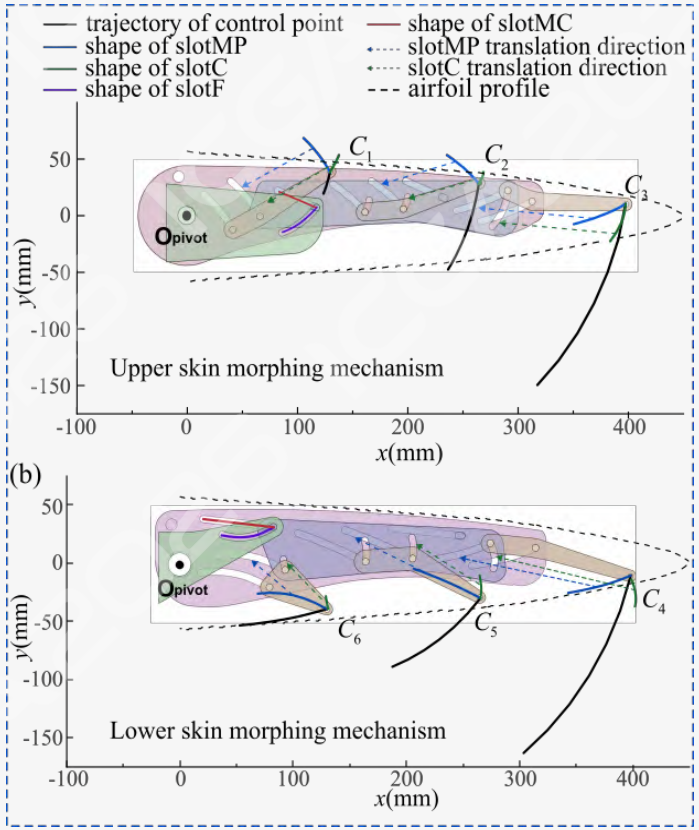
Control points on LE







Closed-chain sliding-slot mechanism



Deformation drive mechanism

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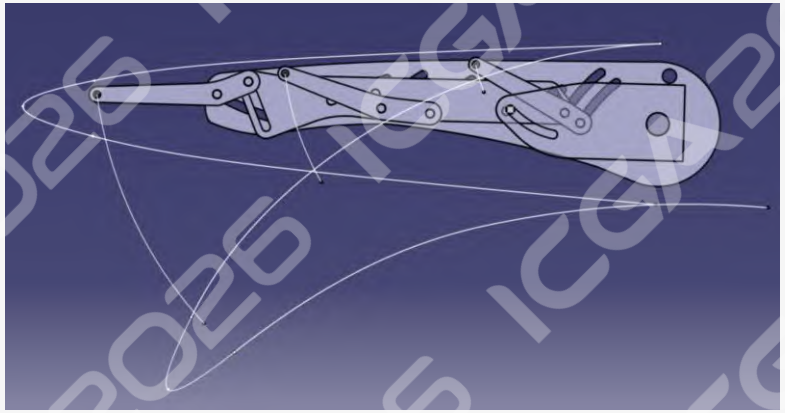
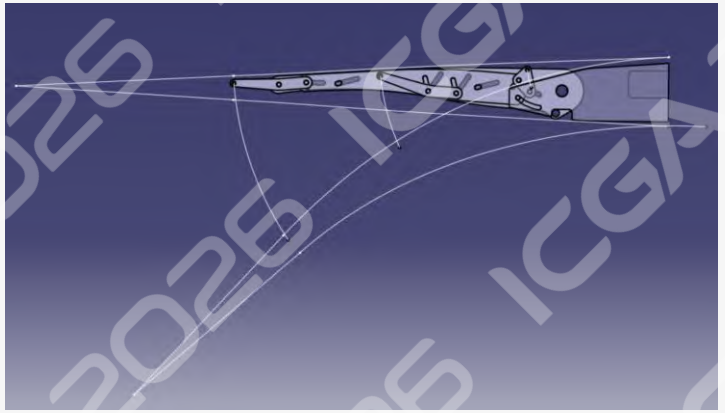
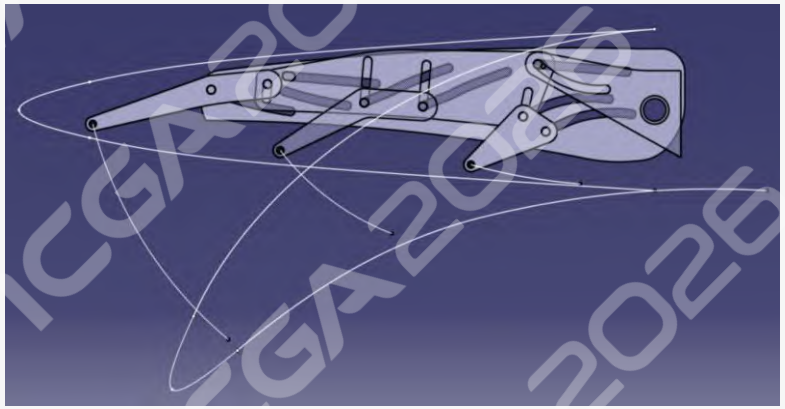
- **Mechanism motion simulation results of the deformation drive mechanism**



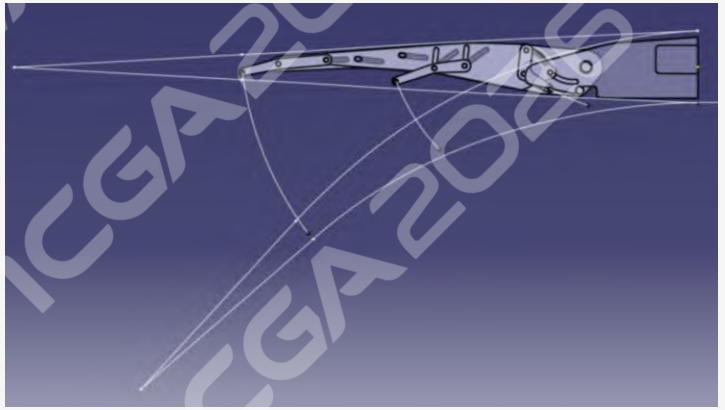
DDM of the upper skin of LE



DDM of the upper skin of TE



DDM of the lower skin of LE



DDM of the lower skin of TE

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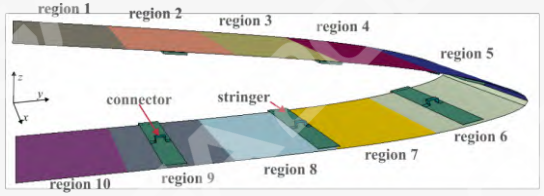
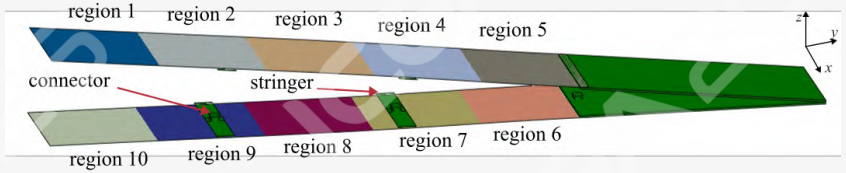
GFRP skin design

- **Variable-thickness GFRP skin: 10 regions**
- **GA algorithm:** design **the skin thickness** in each region to minimize the difference between the deflected shape of the skin under 0.01MPa aerodynamic load and the target deflection profile



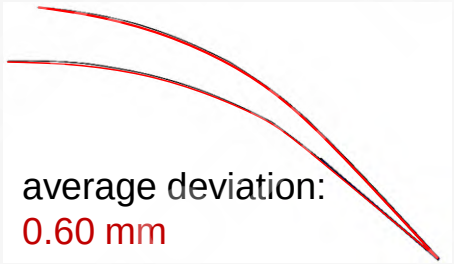
LE skin



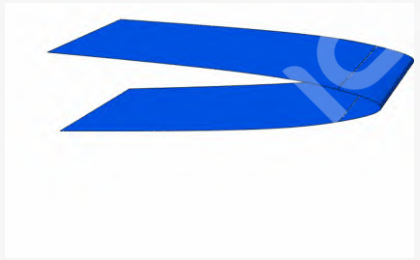
TE skin



average deviation:
0.42 mm



average deviation:
0.60 mm





Skin shape

Airfoil profile

LE skin thickness distribution

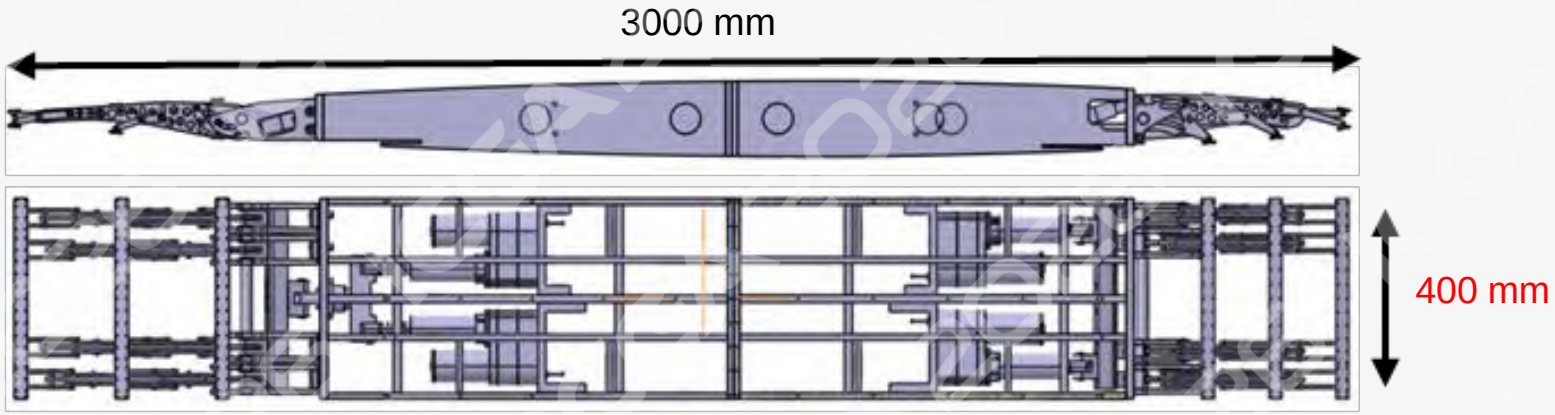
Region	1	2	3	4	5
Thickness (mm)	1.6	0.4	0.8	2.4	1.2
Region	6	7	8	9	10
Thickness (mm)	1.2	2.0	2.0	1.6	2.0

TE skin thickness distribution

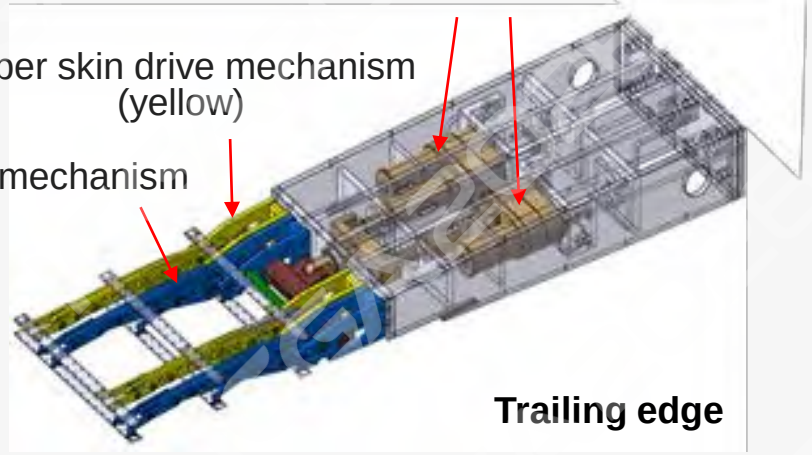
Region	1	2	3	4	5
Thickness (mm)	0.4	0.4	0.5	2.4	2.0
Region	6	7	8	9	10
Thickness (mm)	0.4	2.4	2.0	1.6	2.4

Prototype design

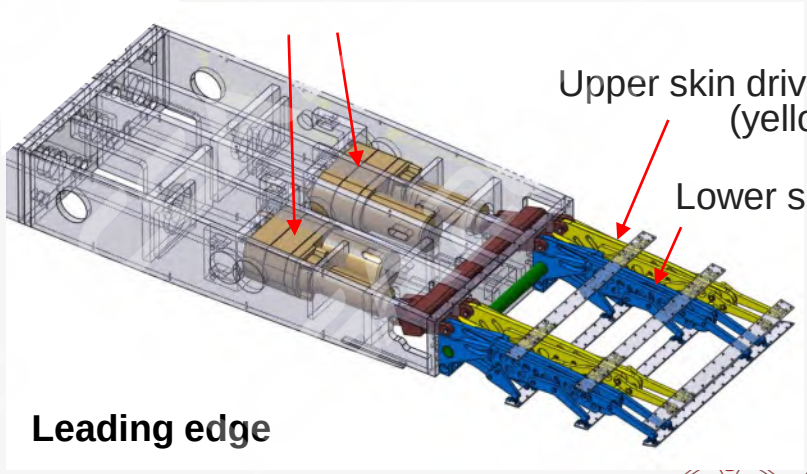
- Span length: **400 mm**
- **Two drive mechanism sets** for TE and LE



Two electric actuators: 8kN force each

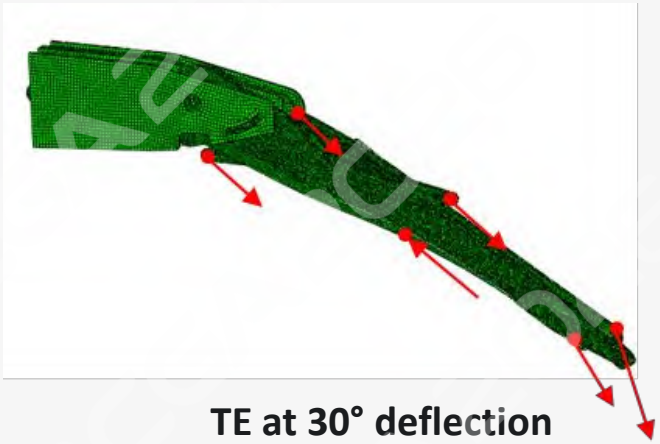


Two electric actuators: 6kN force each

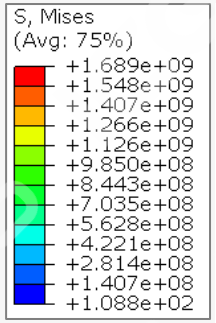


Structure FEM analysis

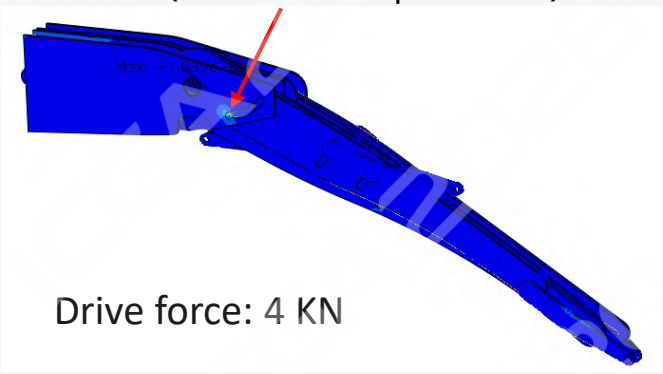
- Apply **0.01MPa** aerodynamic force on the skin

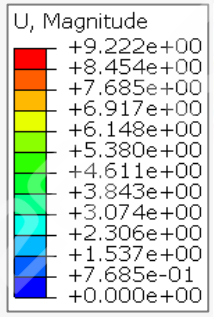


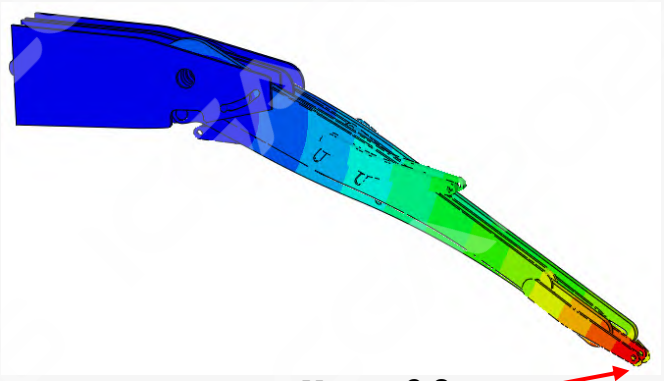
TE at 30° deflection



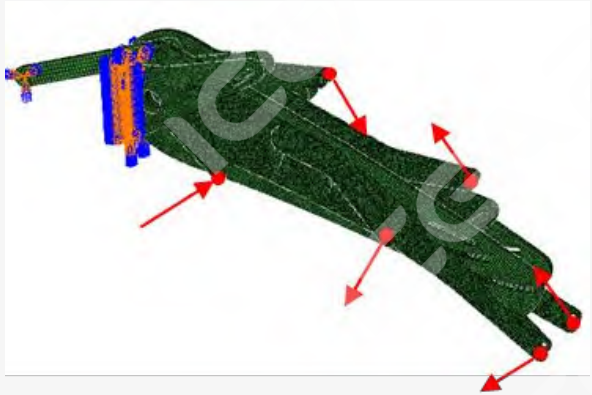
σ_{max}=1689 MPa
(slider on couple beam)



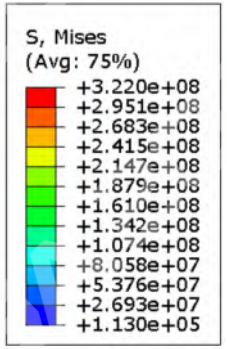




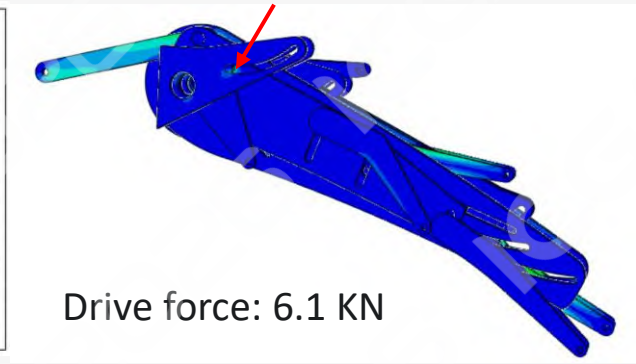
U_{max}=9.2 mm



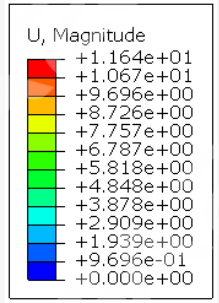
LE at 30° deflection

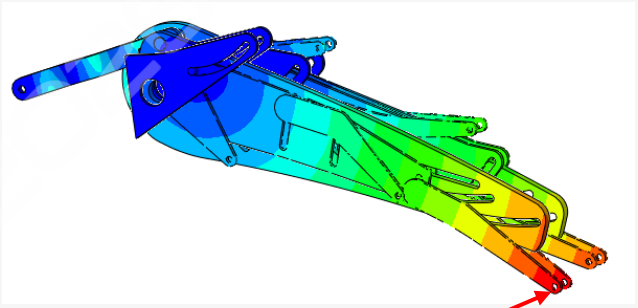


σ_{max}=322 MPa
(slider on couple beam)



Stress contour





U_{max}=11.6 mm

Displacement contour

Prototype test

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Fabricated prototype





LE test



TE test

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Presentation outline

Part I: Structural design of variable-camber wing for supersonic transport aircraft

面向超音速客机的变弯度前后缘机翼结构设计

Part II: An integrated design framework for planar multi-configuration morphing airfoil

平面多维度变形翼机构/结构一体化设计方法

Background

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- Morphing aircraft is a critical technique to achieve efficient cross-domain flight.
- The multi-configuration morphing technology, which integrates multiple morphing modes such as variable camber airfoil, bending and torsion, variable span and sweep, is the key technology to maximize the environmental adaptability of cross-domain vehicle.



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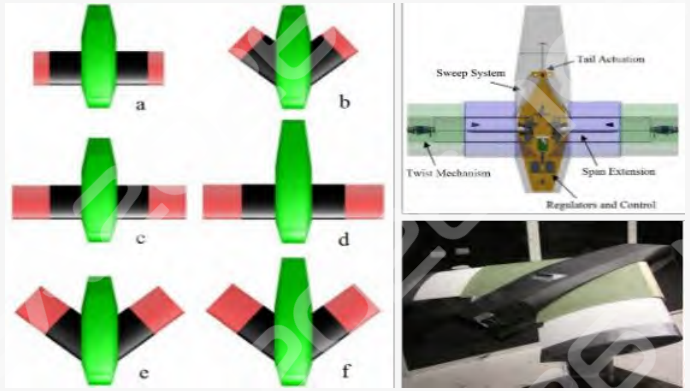
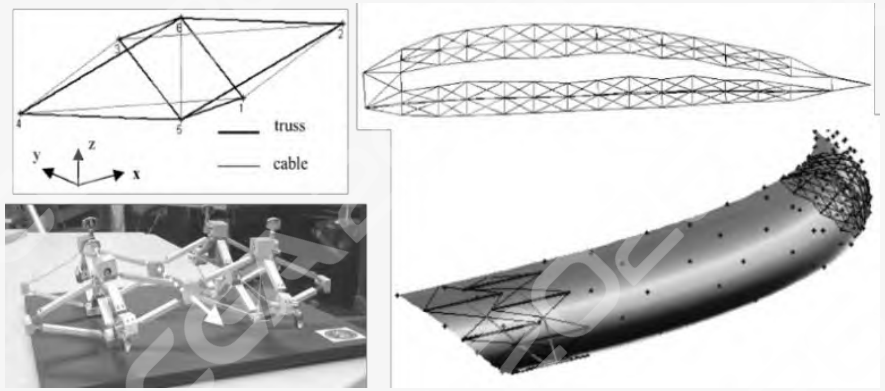
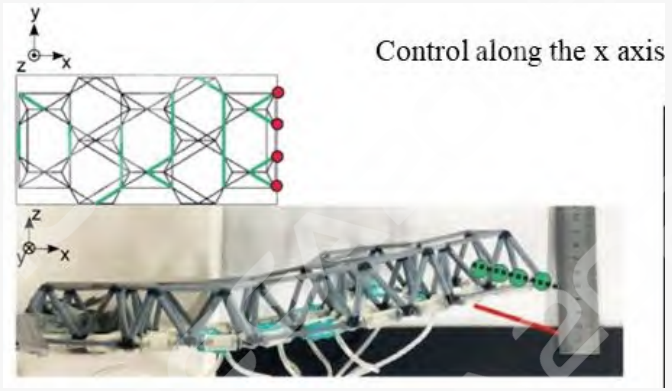
Existing multi-mode morphing technologies



Two-stage morphing wing
by Virginia Tech



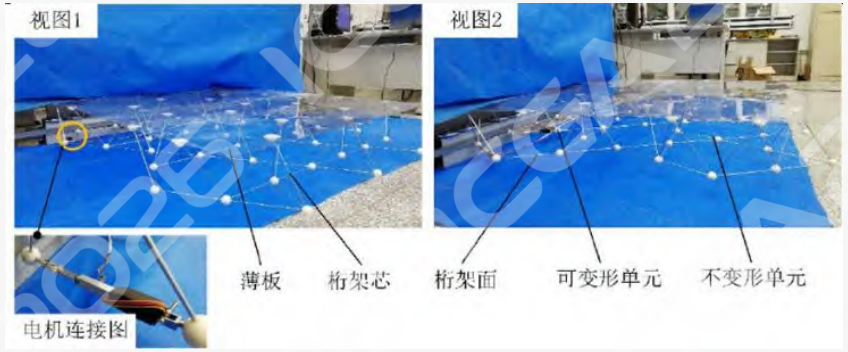
Octahedral-unit morphing wing
by Penn State University



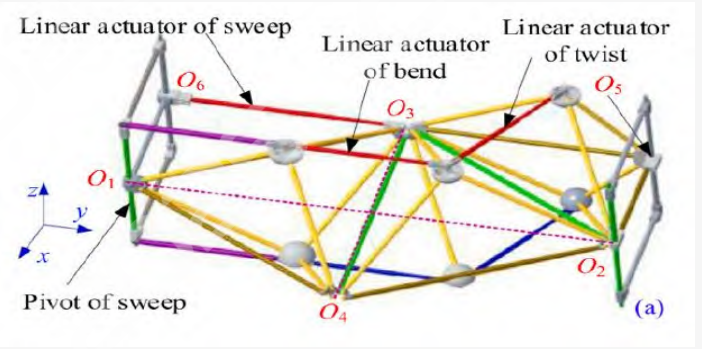
Kagome-unit morphing wing
by ETH Zurich



Tetrahedral-unit morphing wing
by HIT



Kagome-unit morphing wing
by HIT

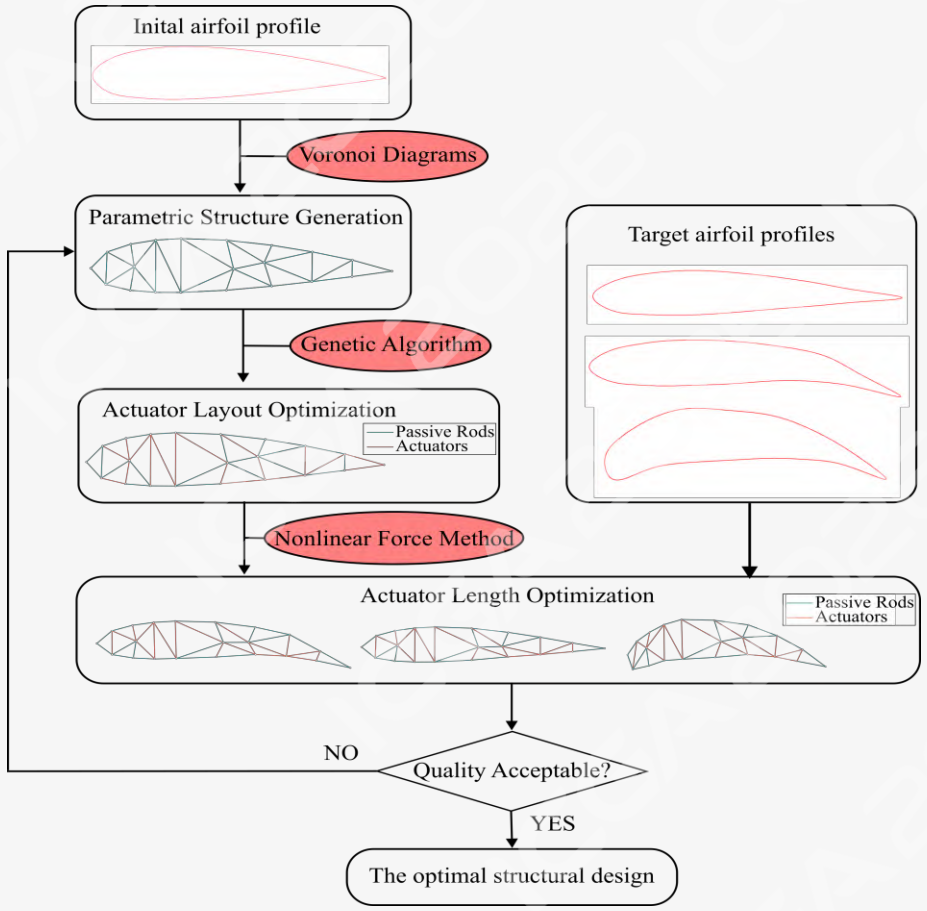


Triangular-pyramid-unit morphing wing
by Yanshan University

The existing multi-mode morphing technologies mainly adopt truss-type morphing mechanisms, which have low adaptability to complex shapes, and are difficult to balance morphing accuracy and load-bearing requirements.

An integrated design framework for planar multi-configuration morphing airfoil

- **An integrated design framework** based on the Voronoi diagram and nonlinear force method: **integrated mechanism-structure design for planar multi-mode morphing airfoil**



- **Key features:**
  - Automatically generate deformable truss structure and actuation layout
  - Strong versatility, applicable to any airfoil shapes
  - Precisely control airfoil surface control points to achieve multi-target morphing

- **Consisting of five core algorithms**

Algorithm 1

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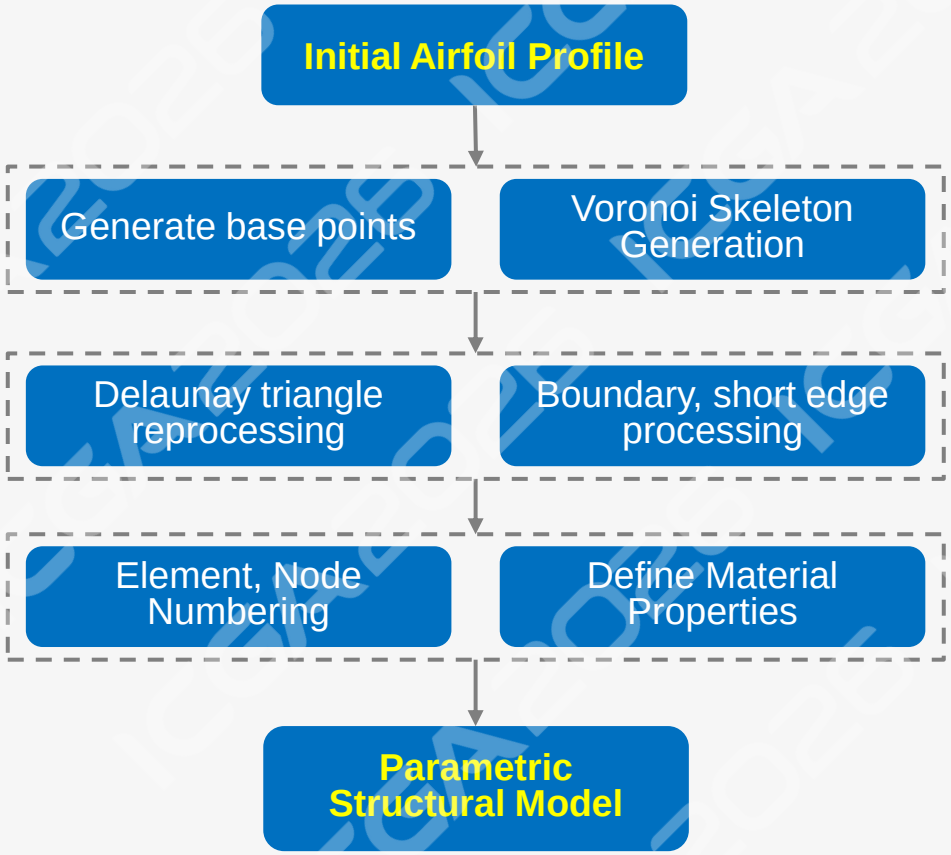
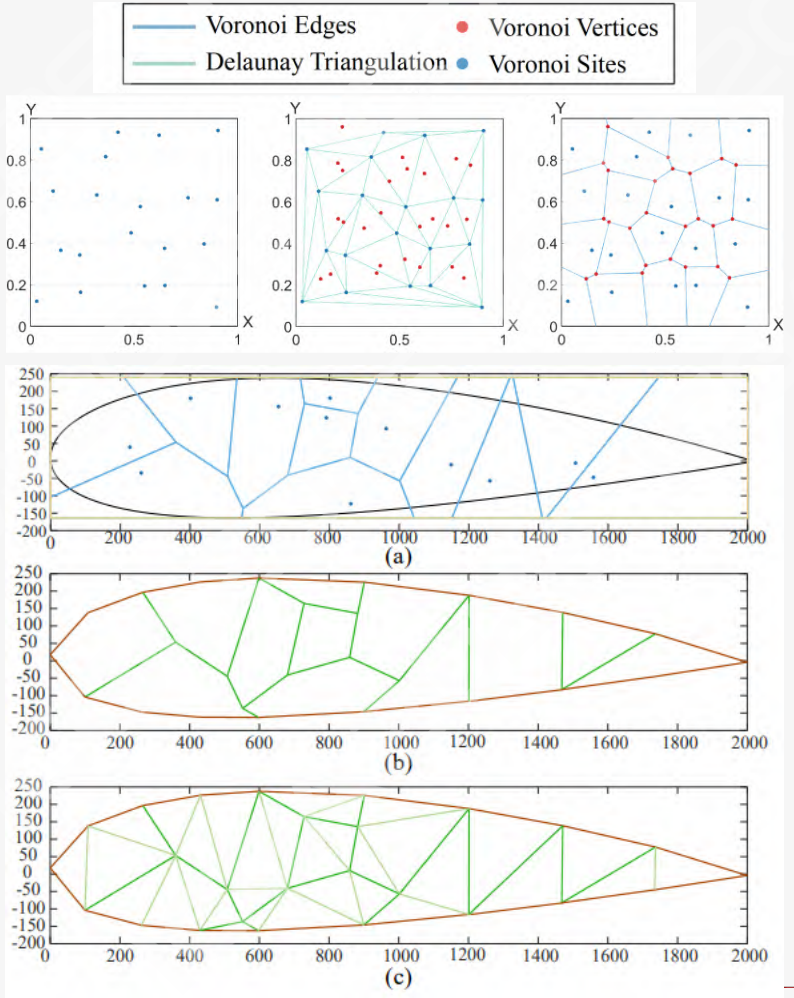
■ **Parametric structure generation method based on improved Voronoi diagram**





Algorithm 2

■ **Finding structural equilibrium state based on nonlinear force method**

Equilibrium equation

$$\mathbf{A}f = P$$

Compatibility equation

$$\mathbf{C}\,\mathbf{d} = \mathbf{e}$$

Constitutive equation

$$e = e_0 + \mathbf{K}f$$

Newton-Raphson method

$$\mathbf{A}^i\,\delta\mathbf{f} = \delta\mathbf{P} \qquad \mathbf{C}^i\,\delta\mathbf{d} = \delta\mathbf{e}$$

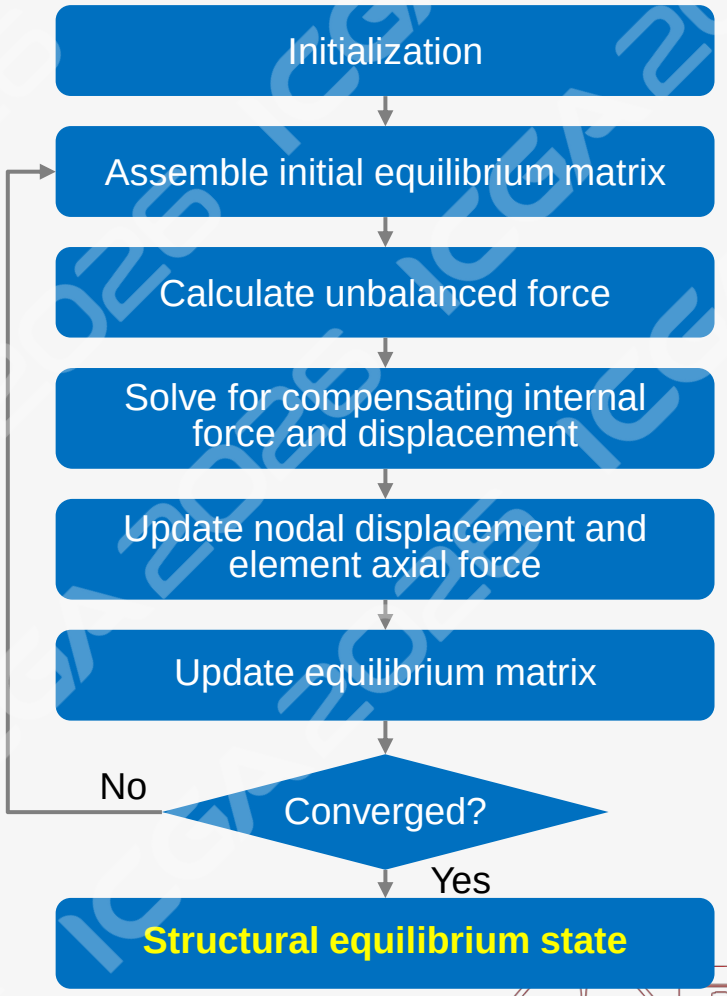
$$\delta\mathbf{e} = \mathbf{K}^i\,\delta\mathbf{f}$$

Singular value decomposition

$$\delta\mathbf{f} = (\mathbf{A})^+\,\delta\mathbf{P} + \mathbf{W}_s\mu$$

$$\mu = (\mathbf{W}_s^{\mathrm{T}}\,\mathbf{K}\,\mathbf{W}_s)^{-1}\mathbf{W}_s^{\mathrm{T}}\,\mathbf{K}\,\mathbf{A}^+\delta\mathbf{P}$$

$$\delta\mathbf{d} = (\mathbf{C})^+\delta\mathbf{e}$$



Algorithm 3

■ **Solving large structural deformation under a given actuation state**

Actuation discretization $\delta e_s \longrightarrow \Delta l/n$

Actuation increment

$$\delta e'^{k}_{s} = \delta e^{k}_{s} + K\delta e^{k}_{s} = [I - KW_s(W_s^T K W_s)^{-1} W_s^T]\delta e^{k}_{s}$$

Increment of actuation per step

Elastic deformation per step

Internal force increment

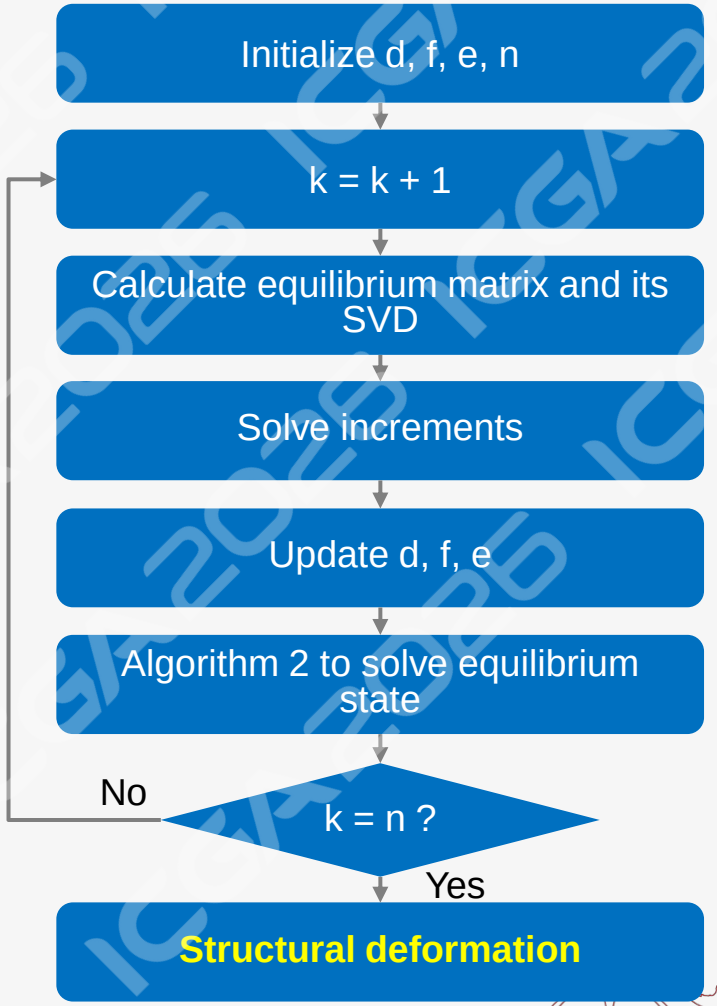
$$\delta f^k = -W_s(W_s^T K W_s)^{-1} W_s^T \delta e^k_s$$

Equilibrium equation

Compatibility equation

Displacement increment

$$\delta d^k_s = B^+[I - KW_s(W_s^T K W_s)^{-1} W_s^T]\delta e^k_s$$



Algorithm 4

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■ **Inverse solving for actuation drive length under a given target configuration**

Control point target displacement update: updates current residual displacement to target displacement

$$\mathbf{d}_t = \mathbf{d}_t - \mathbf{d}_c$$

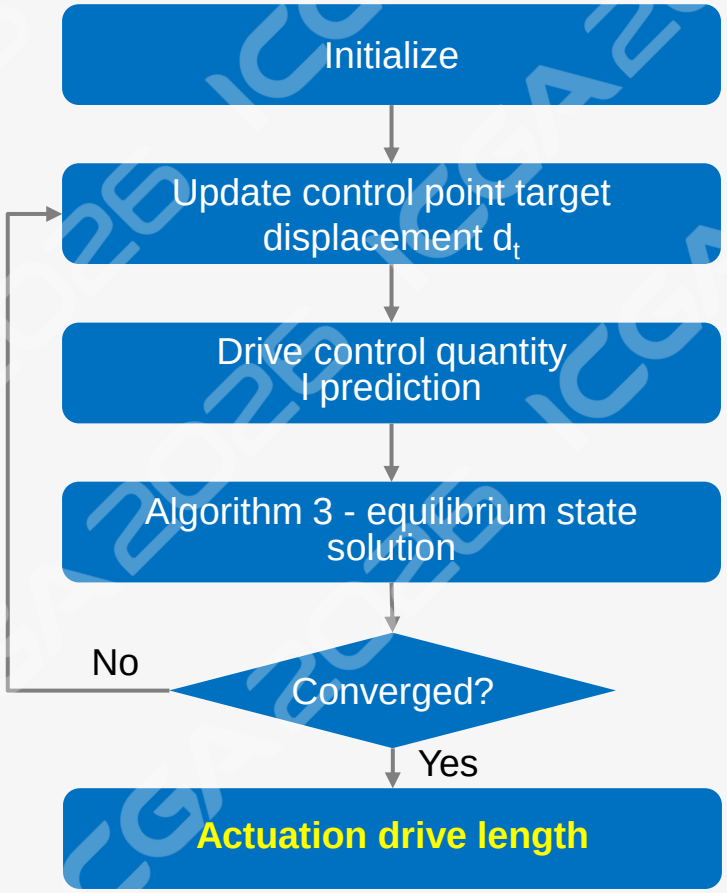
Drive elongation prediction: solves least squares optimization using IPOPT algorithm

$$\min_{\mathbf{l}} \quad \|\mathbf{S}_d\mathbf{l} - \mathbf{d}_t\|_2$$

$$\text{s.t.} \quad l_{\min} \le \mathbf{l} \le l_{\max}$$

Convergence criterion: shape fitting index

$$Q = \frac{(\mathbf{u}_c)^\top \mathbf{u}_t}{(\mathbf{u}_c)^\top \mathbf{u}_c + (\mathbf{u}_t)^\top \mathbf{u}_t - (\mathbf{u}_c)^\top \mathbf{u}_t}$$



Algorithm 5

■ **Optimization of actuation layout for multi-target morphing configurations**

Driving efficiency of the *i-th* rod for the *j-th* target configuration

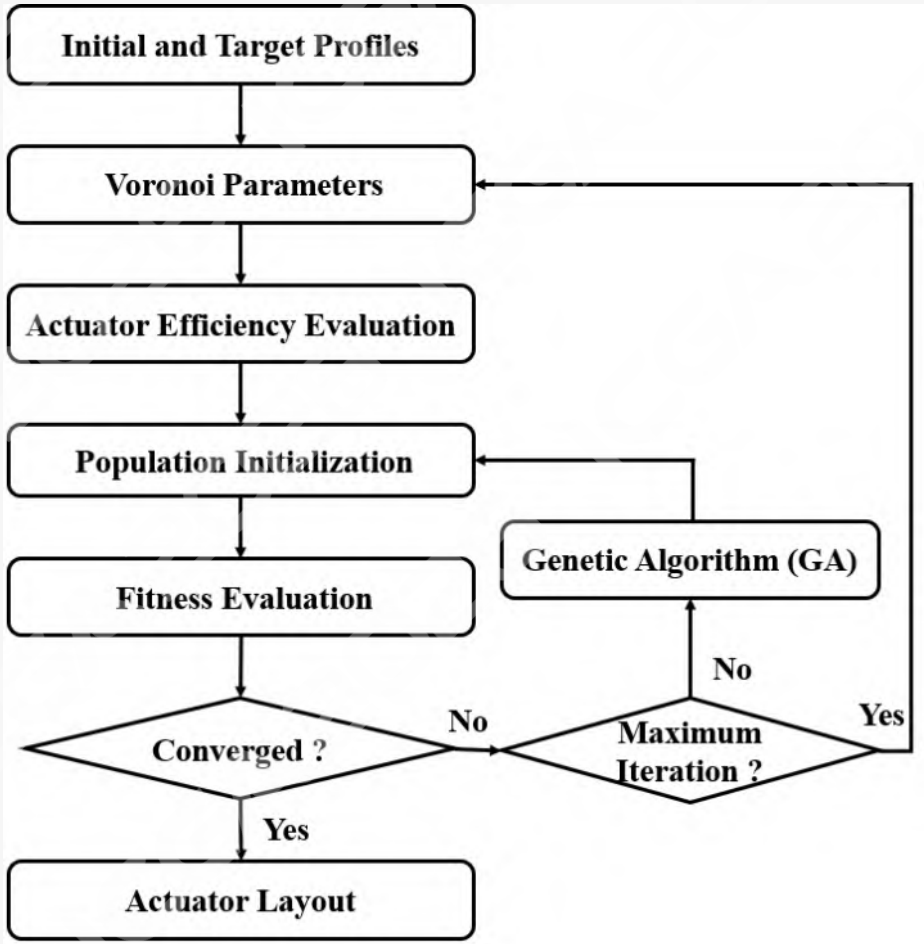
$$E_i = \frac{\sum_{h=1}^{n^{cDOFs}} \left(\mathbf{S}_h^{ulcDOFs} \cdot \Delta \mathbf{L}_i\right) \circ \frac{1}{\mathbf{u}_j^{cDFFs}}}{n^{cDOFs}}$$

Fitness of the *j-th* target configuration:

$$\hat{Q}_j = \frac{Q_j - Q_j^{min}}{Q_j^{max} - Q_j^{min}}$$

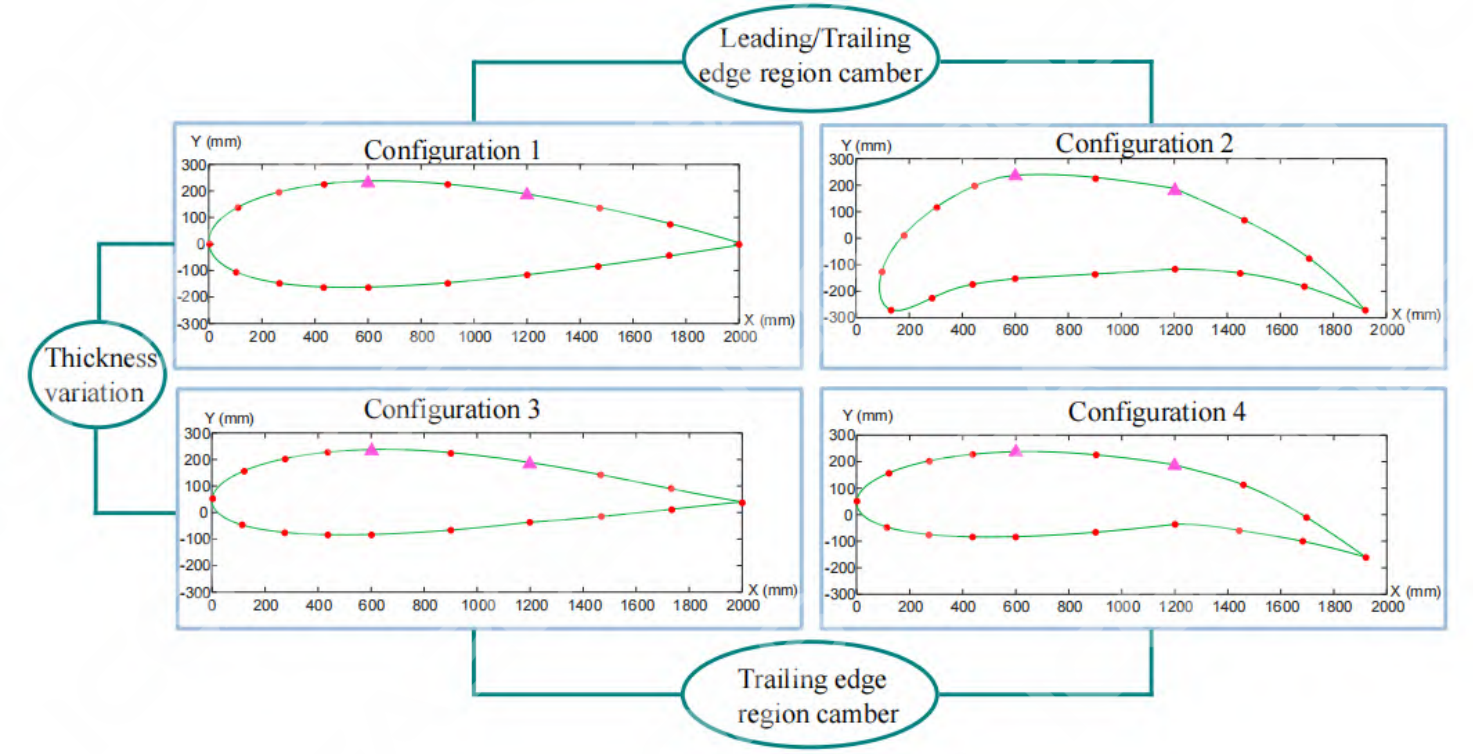
Comprehensive fitness:

$$F(\mathbf{x}) = \left(\prod_{j=1}^{k} \hat{Q}_j\right)^{1/k}$$



Case study

- **Design objective: continuous shape morphing between four airfoil configurations**
  - **Configuration 1 to 2**: 30° downward deflection of TE and LE
  - **Configuration 1 to 3**: 20% thickness reduction
  - **Configuration 3 to 4**: 30° downward deflection of TE



Case study

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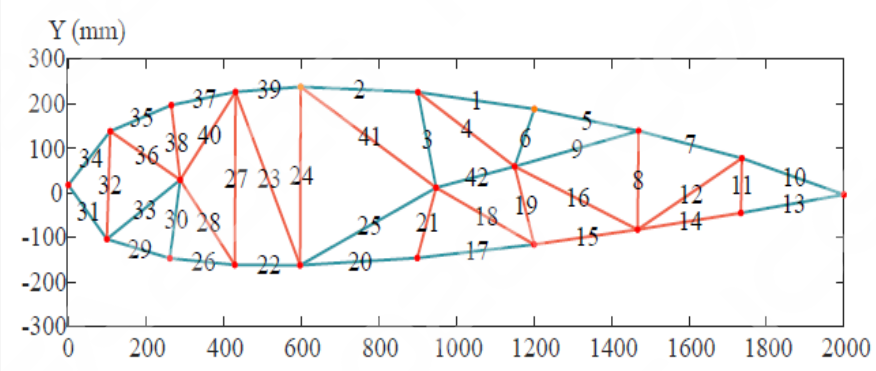
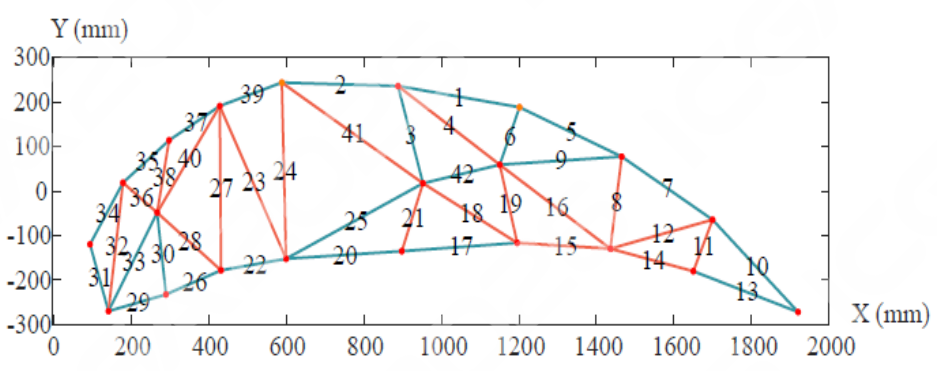
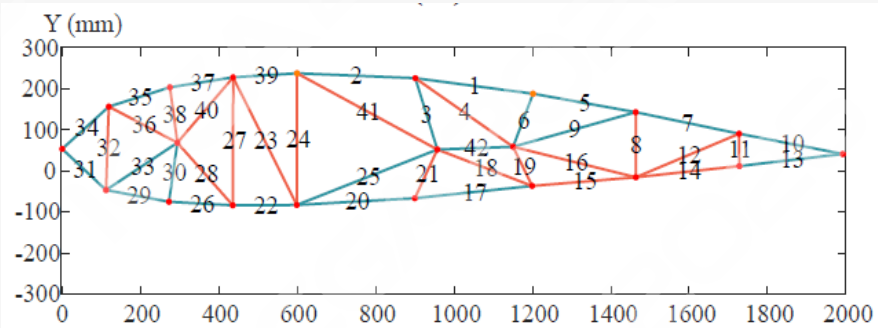
- **Design results: 16 surface control points, 19 actuation rods (red), 23 passive rods (blue)**
- Max drive stroke: 46.8%
- Shape fitting index Q ≥ 0.99



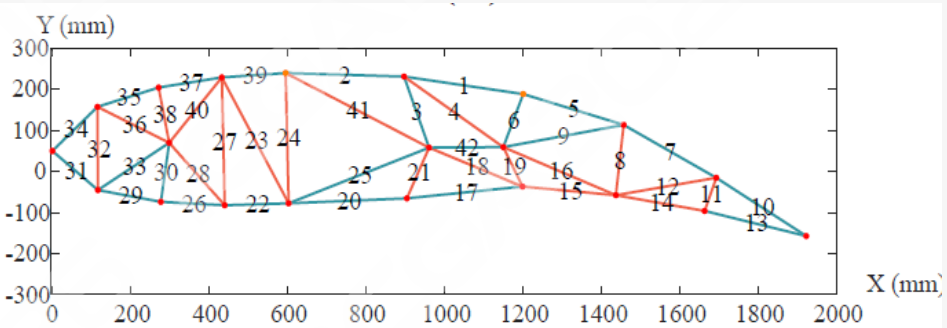
configuration 1



configuration 2



configuration 3



configuration 4

Case study

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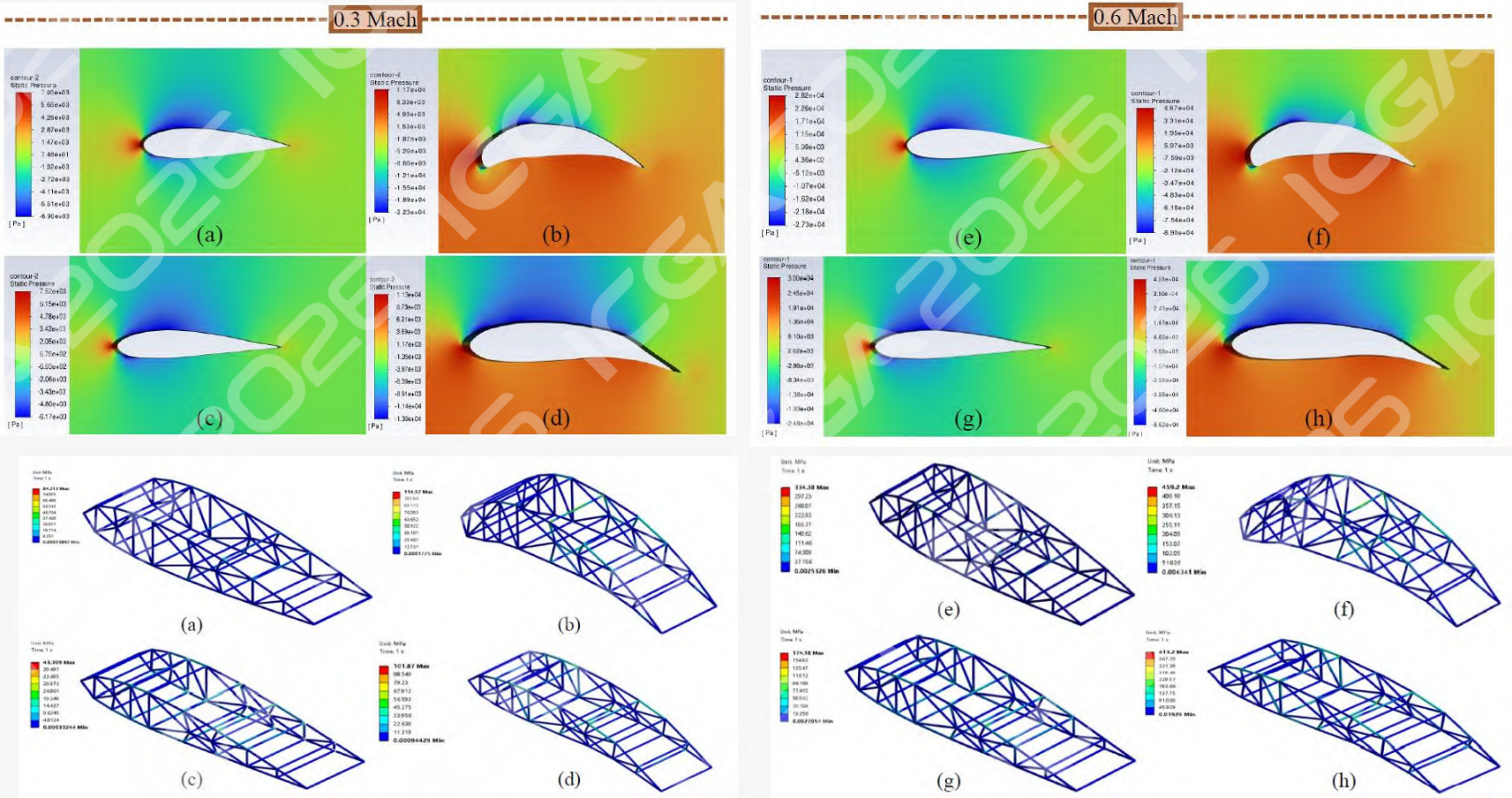
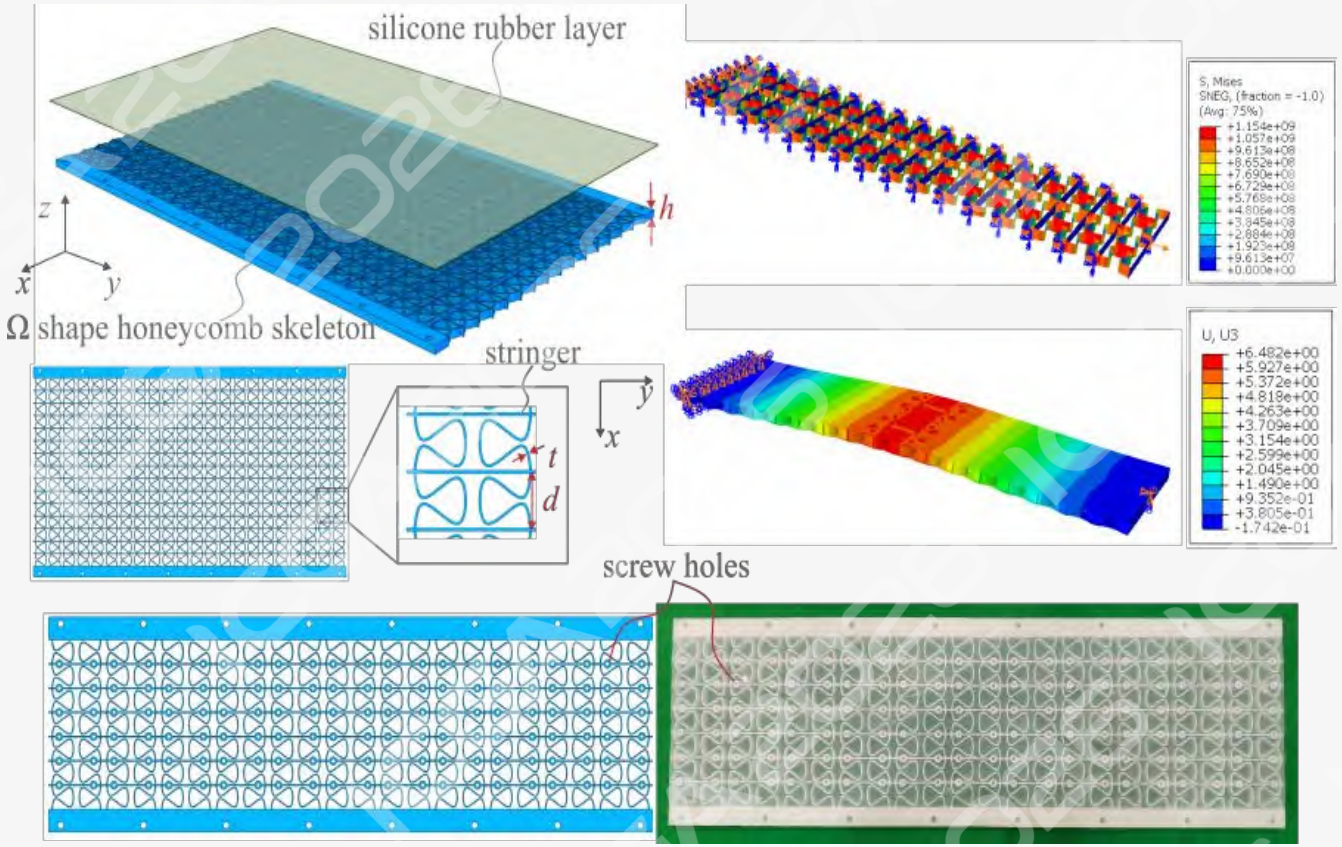
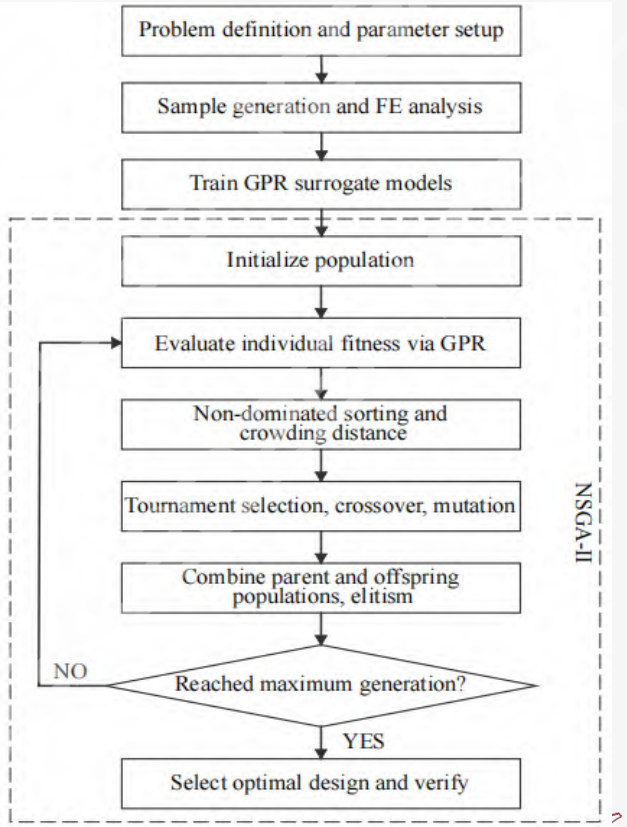
- **Fluid-structure analysis: velocity ~ Mach 0.3 and 0.6, structural material ~ 7075 Al**
  - Max stress: 459 MPa



Case study

- **Flexible skin design: Ω-shaped honeycomb skeleton + silicone rubber external skin**
  - **Skeleton structure optimization**: GPR surrogate model + NSGA-II multi-objective genetic algorithm
  - **Optimization target**: minimize the in-plane drive force and out-of-plane deflection

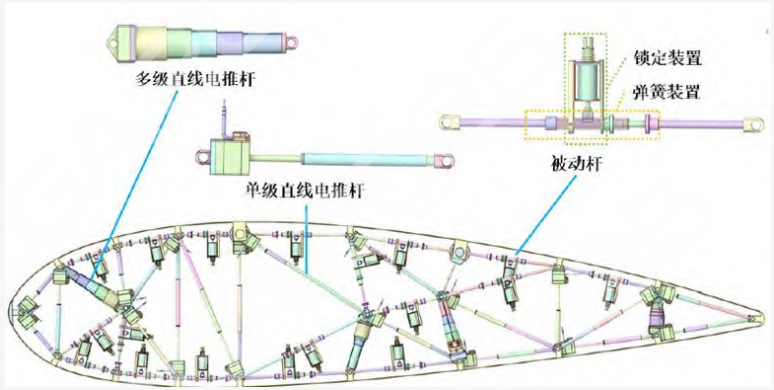


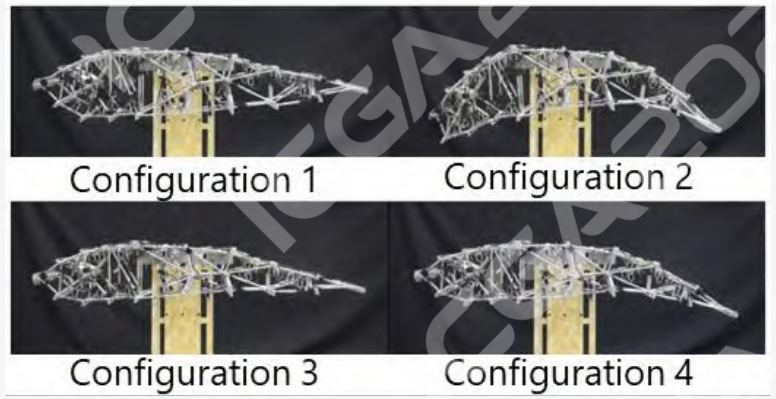


Case study

- **Protype design and test: chord length 2m, span 0.5m**
  - **Actuation rod**: electric linear actuator
  - **Passive rod**: electromagnetic latch

	构型 1		构型 2		构型 3		构型 4	
误差类型	sim	exp	sim	exp	sim	exp	sim	exp
ϵ^{max} (mm)	0.0	14.2	2.4	28.5	1.3	25.1	1.4	22.7
ϵ^{mean} (mm)	0.0	9.7	1.1	19.6	0.9	14.8	0.9	14.4







Summary

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Structural design of variable-camber wing for supersonic transport aircraft

- Designed a variable camber wing structure with closed-chain sliding-slot mechanism and variable-thickness GFRP skin.
- LE and TE can have 30° downward deflection.
- A prototype of 3m chord length was fabricated and tested.

An integrated design framework for planar multi-configuration morphing airfoil

- An integrated design framework based on the Voronoi diagram and nonlinear force method was developed for the mechanism-structure design for planar multi-configuration morphing airfoil.
- A prototype of 2m chord length with four different configurations was designed and fabricated.

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Collaborators

- Tianjian Jiang, Xinyuan Niu, Dr. Keyao Song, Prof. Xiasheng Sun, Dr. Yu Yang, Prof. Hongwei Guo

Publications

- Jiang, T., Song, K., Niu, X., Sun, X., Zhao, D., Li, J. and Zhou, X. A generalised inverse-design framework for variable camber wings: A supersonic thin airfoil case study. *Aerospace Science and Technology*, 176 (2026): 113545.
- Jiang, T., Song, K., Cheng, G., Niu, X., Yang, Y., Guo, H. and Zhou, X. A generic and integrated design framework for multi-configuration morphing wing structure. *Smart Materials and Structures*, 35 (2026): 105015.

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Thank you!