# Aerodynamic Analysis of Morphing Airfoils under Steady and Unsteady Inflow Conditions

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## Research Question

How can adaptive morphing airfoils reduce unsteady aerodynamic load variations under gusty inflow conditions?

## Background and Objectives

Aircraft wings experience unsteady loads from gusts. Morphing airfoils can adapt their shape to enhance stability and efficiency.

The objectives are to:

- Develop variable-camber morphing airfoil geometries.
- Simulate steady and unsteady conditions using URANS in OpenFOAM.
- Analyze aerodynamic performance for different morphing amplitudes

## Obstacles Faced

Simulating dynamic mesh motion in OpenFOAM was difficult, as maintaining mesh quality during morphing caused solver instability. Near-wall refinement required several mesh adjustments, and simulation runs were time-intensive, limiting the number of morphing cases tested.

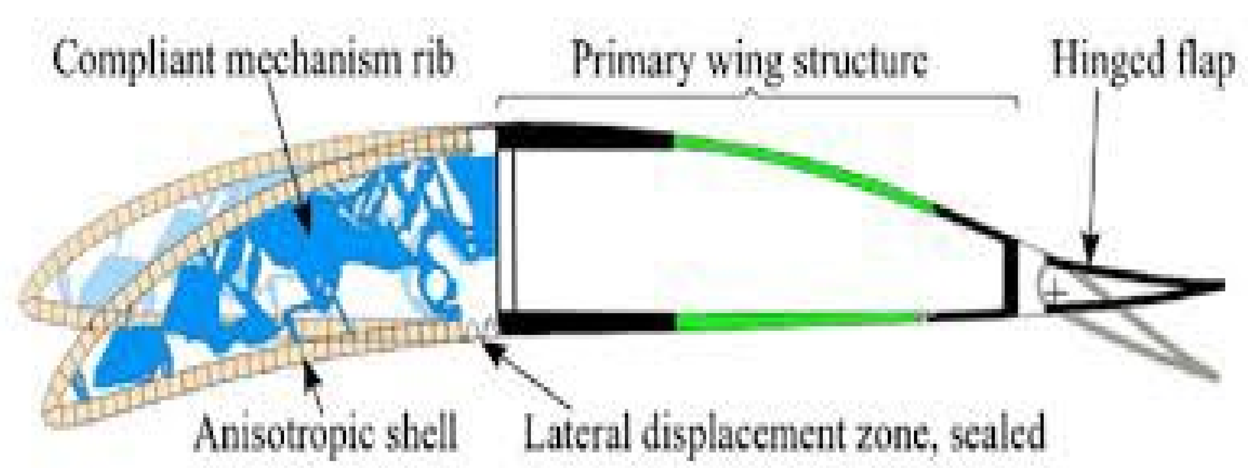


Figure 1: Morphing Airfoil Schematic

## Methodology and Simulation Setup

Morphing airfoils were generated using a Python script that applied smooth deformation fields to a baseline NACA 0012 geometry. Polynomial and harmonic shape modes were combined to create multiple camber configurations in OpenFOAM[1,2].

$$y_m(x,t) = y_{base}(x) + A_m[\alpha_1(x - x_p)^2 + \alpha_2 \sin(\pi x) + \alpha_3 \sin(2\pi x)]\phi(t)$$

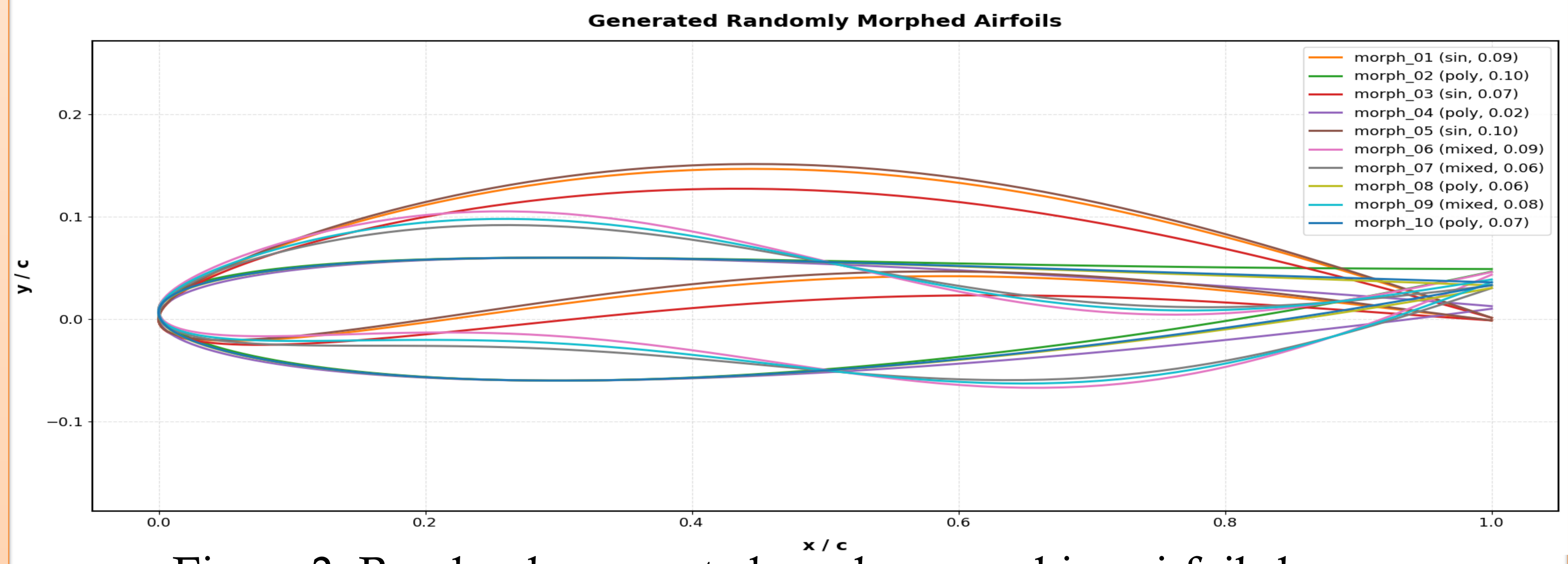


Figure 2: Randomly generated camber-morphing airfoil shapes

RANS simulations at $Re = 1 \times 10^6$ under steady inflow were initially used to study morphing airfoil aerodynamics. Variations in morphing amplitude affected flow structure and lift, providing a baseline for future LES studies under gusty conditions.

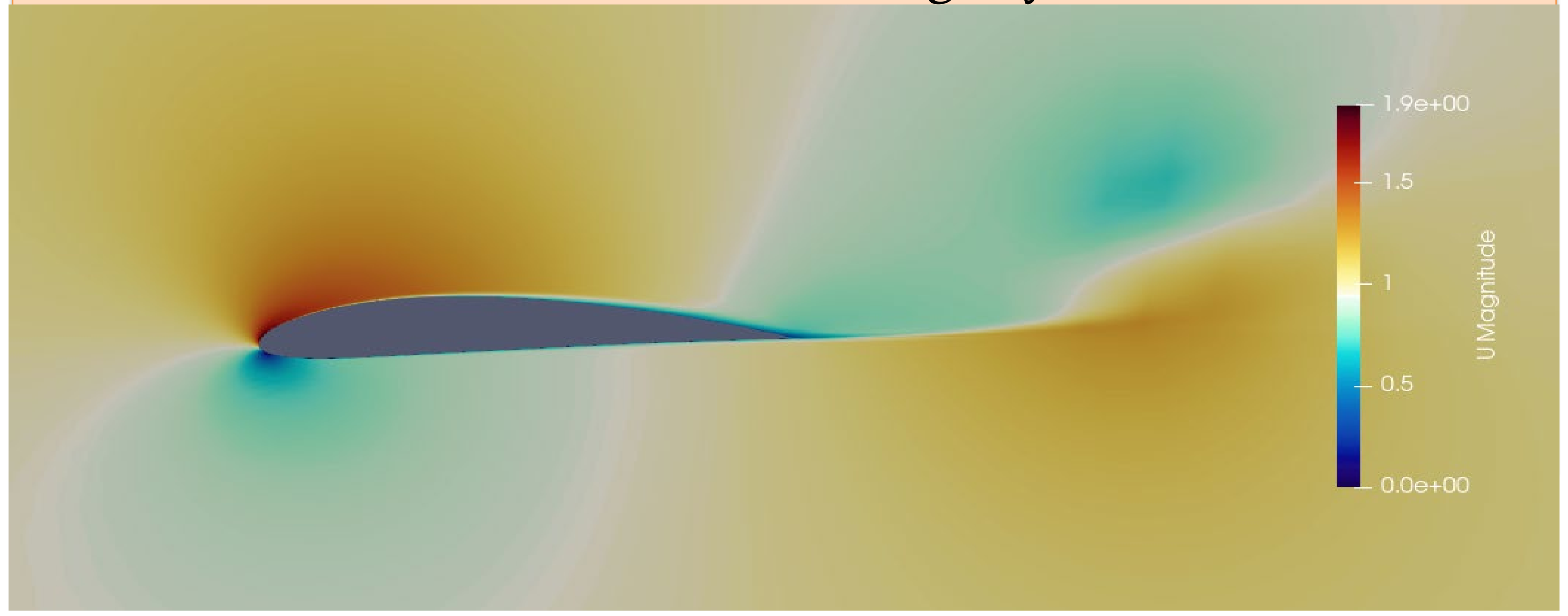


Figure 3: Velocity magnitude contours around the morphing airfoil

## Results and Future Work

Steady-state RANS simulations of morphing airfoils ($A_m = 0.02c$–$0.08c$) were performed in OpenFOAM under uniform inflow conditions. Increasing morphing amplitude improved aerodynamic performance, consistent with previous findings in adaptive camber research[1]. Compared to the baseline case $A_m = 0$, the morphing airfoil with $A_m = 0.08c$ showed a mean lift $C_L$ increase from 0.85 to 0.92 (≈8%) and a mean drag $C_D$ decrease from 0.065 to 0.060 (≈9%). Future work will focus on performing Large-Eddy Simulations (LES) under unsteady gust inflow using velocity profile[3]:

$$U(t) = \bar{U}(y)\left[1 + A_g \sin(2\pi f_g t)\right] + u'(t)$$

to study transient flow behavior and associated unsteady loads. Further objectives include analyzing time-dependent lift and drag responses, vortex shedding, and gust–airfoil interaction to identify morphing designs effective for gust-load alleviation.

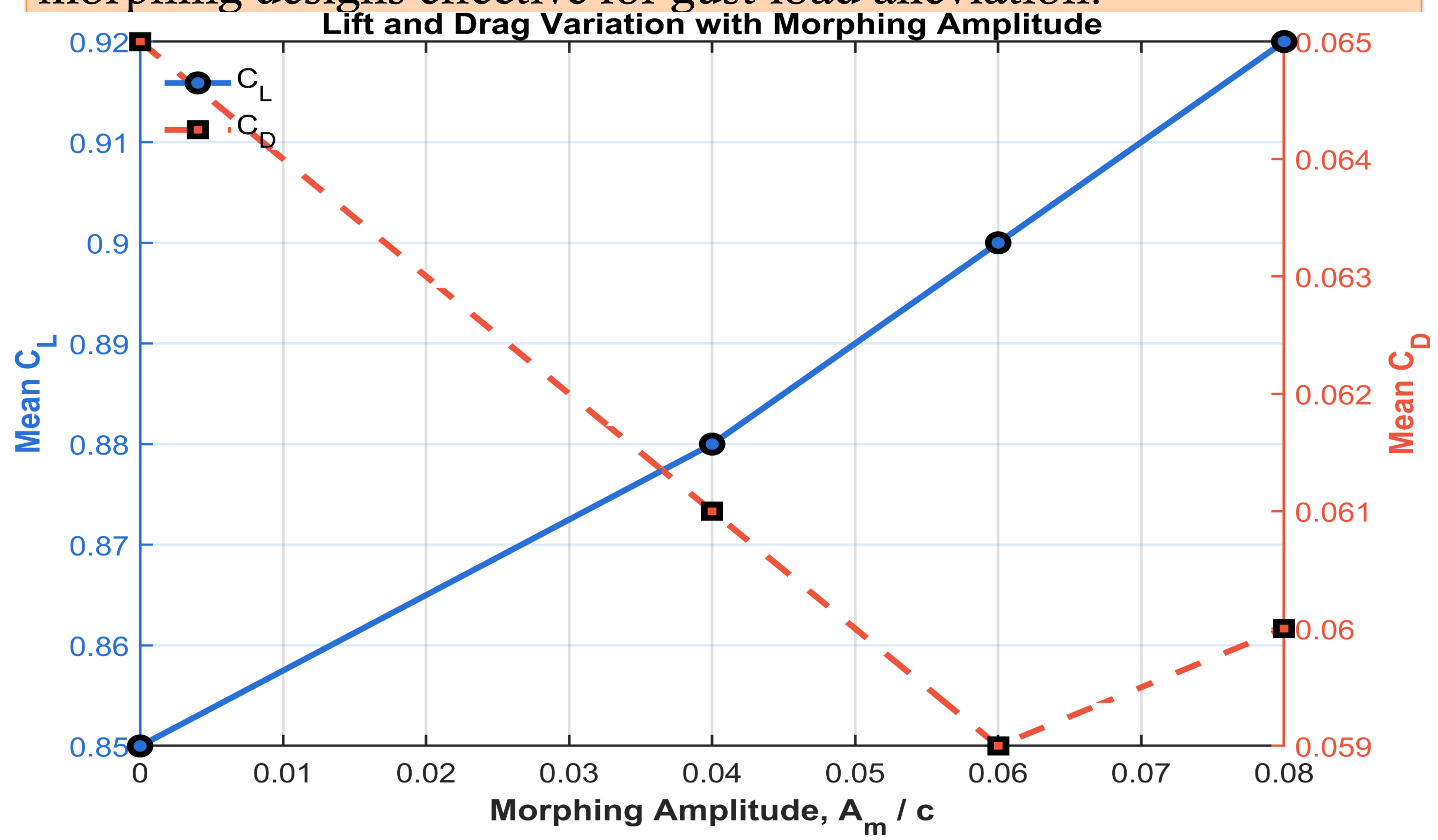


Figure 4: Variation of mean lift and drag coefficients with morphing amplitude

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References

1. **Kim, D., Yoon, S., & Rho, J. (2021).** *Aerodynamic Load Alleviation of Adaptive Camber Airfoils under Gust Inflow Using LES.* **AIAA Journal**, 59(9), 3587–3601.
2. **Sharma, N., Pal, A., & Singh, R. (2020).** *Unsteady Flow Characteristics of a Camber-Morphing Airfoil Using CFD.* **Journal of Fluids and Structures**, 95, 102985.
3. **Schlüter, J. U., Pitsch, H., & Moin, P. (2024).** *Large-Eddy Simulation Inflow Conditions for Coupling with Reynolds-Averaged Flow Solvers.* **AIAA Journal**, 42(3),

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