BTP
Bio-inspired Morphing Wing Design

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Introduction

Biomimicry has been prevalent in engineering since long, and is getting even more popular in recent times. This work takes inspiration from a dragon wing.

Dragonfly wing are corrugated in nature, meaning they have "**zig-zag**" like cross section structure.

This corrugation helps in increasing bending stiffness while maintaining light wing weight, which is needed in flapping wing insects

In this study, we will look into the gliding mode of dragonfly only.

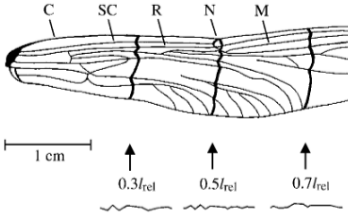


Figure: Forewing of *Aeshna Cyanea*

Figure: *Aeshna Cyanea*

Why Dragonfly?

But Gliding, Dragonflies??
only two flapping wing insects, **Butterfly** and **Dragonfly** are known to alternate powered flapping flight with periods of gliding primarily to save energy

- Dragonfly *Aeshna Cyanea* can glide for 30 seconds, without significant altitude loss
- *Pantala flavescens* is migratory dragonfly known for crossing large water bodies like **Indian Ocean** recording about **18,000 km**
- If looked carefully, even small dragonflies found in campus usually glide for 0.5-1 s while flapping (saves energy!)

Goal

- To investigate the feasibility of **morphing in corrugated wings** as a passive or semi-active strategy to enhance aerodynamic performance, with a focus on:
  - Increasing C_L/C_D
  - Reducing drag coefficient (C_D)
  - Improving lift coefficient (C_L)
  - Exploring potential for gust load alleviation

- **Scope of Study:** Although a dragonfly possesses four wings (two forewings and two hindwings), this study is restricted to the **forewing only** to isolate and clearly understand the morphing effects.

Apporach

- To study the aerodynamics of the corrugated wing structure
- To verify if dragonfly wings are optimized for aerodynamics/gliding
- If they perform reasonably well in glide mode, we will go ahead plan of designing a morphing wing structure
- Choosing a morphing strategy
- Analyse the performance of the selected morphing mechanism

Potential Applications

- These type of corrugated wings find their way in flapping wing MAVs
- Since flapping consumes a lot of energy, at least 3-5 times or more. And due its size limitation, it can't use bigger batteries to last long. Most MAV currently can fly for about 3-15 minutes, which is very less.
- Incorporating phases of gliding in flapping can greatly improve endurance by approximately **3-6 times**

Methodology

Dragonfly *Anax parthenope julius* was chosen for the study even though *Aeshna Cyanea* is a better known glider

Reason

- The profiles of both species had very close resemblance at similar spanwise locations
- Okamoto's team has done experimental studies on *Anax parthenope julius*, giving us real data to validate our results

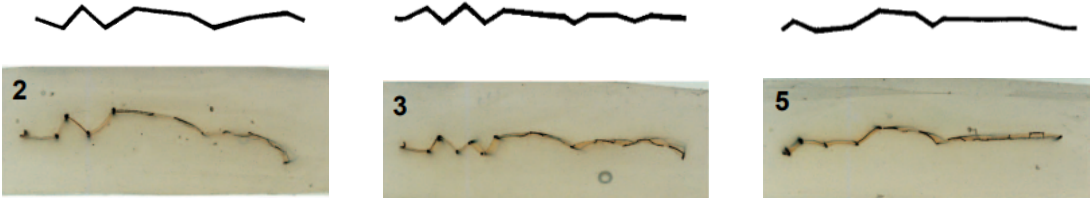


Figure: Profiles of *Aeshna Cyanea* (upper) vs.*Anax parthenope julius* (lower)

Initial Aerodynamic Analysis (BTP-1)

- Two types of aerodynamic analyses were performed:
  - **2-D simulations**
  - **3-D simulations**
- For the 2-D study, simulations were conducted at **five spanwise locations**:

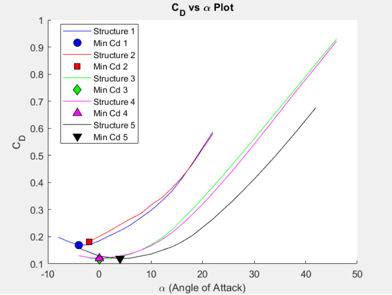
$$0.16l_{rel},\ 0.30l_{rel},\ 0.45l_{rel},\ 0.60l_{rel},\ 0.75l_{rel}$$

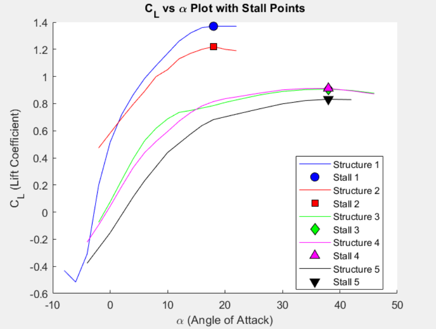
- A mesh convergence study was attempted; however, due to hardware limitations, the mesh was restricted to a minimum element size of **0.5 mm**.
- The freestream velocity was maintained at **3 m/s**, resulting in a Reynolds number of:

$$Re \approx 1230$$

2-D Simulation Plots

- Stall characteristics are gradual, mostly due to low reynolds number
- Minimum C_d is observed near 0^o angle of attack, probably due to minimum projected area (as seen from the direction of freestream)



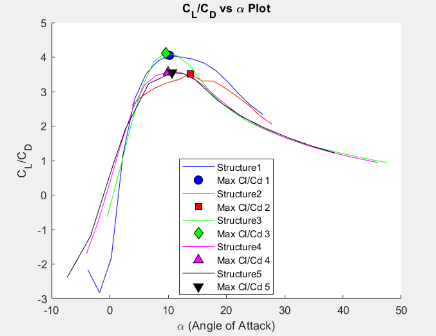


2-D Simulation Plots

- The C_l/C_d curve, for all the strucutres tned to peak at around 10-15 degrees, in line with existing literature
- Dragonfly wings are known to undergo passive twist due to aerodynamic leads, whihc is believed to increse its performace, this twist is known to be around 10-15 degrees

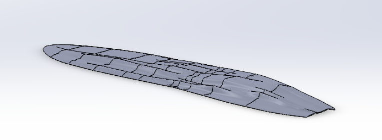
Table: AoA corresponding to maximum C_l/C_d for each profile of *Aeshna Cyanea*

Profile	**AoA for max C_l/C_d**
1	10.25
2	10.32
3	10.31
4	10.74
5	13.14



3-D Setup

- The profiles at 5 spanwise location were used to create a 3-D wing using **Boundary Surface** feature in SolidWorks, which is kind of interpolation of the surface between two profiles
- A thickness of 0.05mm was chosen, **10 times** the actual thickness, due to software limitaions



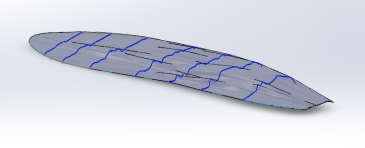
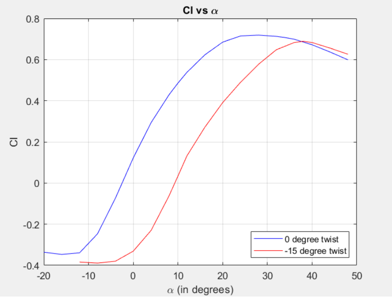
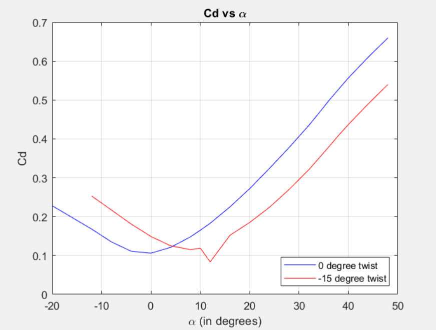


Figure: CAD of wing with -15° (left) and -15° (right) twist

3-D Results

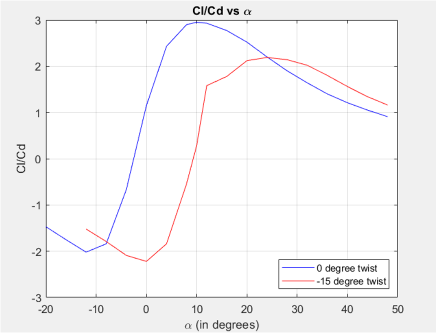
- Change of twist just shifts the curve laterally for both C_l and C_d
- There is a slight increase in C_L for 0^o twist, but that is not so significant





3-D Results

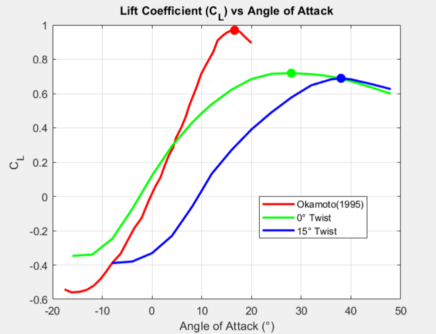
- The C_L/C_D curve shows a lateral shift like C_l and C_d curves
- There is an increase in maximum C_L/C_D as we go from -15^o to 0^o twist



C_l/C_d vs α for two different twists

Validation

- The 3-D wing results were compared with Okamoto (1995)
- This comparison just gives a rough estimate because:
-
    - We don't knowing the actual twist in wing used in the experiment
    - There is a slight difference in Reynolds number, 1230 vs. 1500



Comparison of the results with Okamoto(1995)

Initial Inferences

- Corrugated wings are reported in literature to exhibit **favourable stall characteristics**, often outperforming smooth airfoil profiles. This trend is also partially supported by our simulation results.
- The maximum C_L/C_D was consistently observed in the angle of attack range of **10–15**$^\circ$, aligning well with established aerodynamic behaviour of corrugated profiles.
- 3-D simulation results were compared with experimental data from **Okamoto (1995)**. Although the results did not perfectly align, the deviation was moderate and within an acceptable range.
- Overall, both literature and our analysis indicate that corrugated wings possess promising aerodynamic characteristics. This motivates the next phase of this work, which focuses on **wing morphing** to further enhance aerodynamic performance.

Wing Morphing : Possible Strategies

Different approaches can be adopted to achieve wing morphing:

- **On-wing actuators:** Actuators mounted directly on the wing structure
  (Adds significant weight and complexity to the wing)
- **Remote actuation with link mechanisms:** Motion transmitted using mechanical linkages from actuators located in the fuselage
  (Mechanically complex and often provides limited control authority)
- **Fluidic pressure actuation:** Morphing achieved by varying pressure in embedded fluid-filled structures, with the pump located in the body
  (Well-suited for lightweight, small-scale wings such as in our case)

Wing Morphing : Concept Overview

The core idea is to use **fluid-filled corrugated tubes** as the 2D cross-sections of the wing structure. By varying the internal pressure within these tubes, the wing shape can be altered.

This strategy exploits a well-known phenomenon:

- Bent pipes tend to **unbend / straighten** when the internal pressure is increased.

This effect is visually analogous to the behaviour of a party blower, where inflation causes straightening.

Analogy between party blower and unbending of pressurised curved tubes

Wing Morphing : Literature Background

There exists literature on the *unbending of thin-walled pipes due to internal pressure*. However:

- Most studies rely on **small strain assumptions**
- These are not suitable for morphing, where large geometric changes are required

A limited number of works address large deformation behavior using **neo-Hookean material models**. One such significant study by *Kolesnikov et al.* establishes a relationship between:

- Normalised curvature (B)
- Normalized Internal pressure (p)

The paper formulates a mathematical model and computes the response for different tube geometries and initial curvatures.

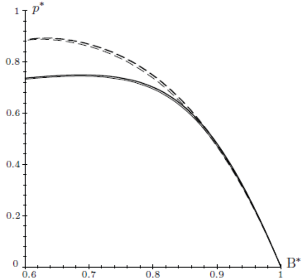
Wing Morphing : Non-monotonic Behaviour

Interestingly, the pressure-curvature relationship is **non-monotonic**.

Instead of steadily increasing pressure for decreasing curvature, the curve exhibits:

- A **maximum pressure** at an intermediate curvature
- Beyond this point, further straightening occurs at **lower pressure**

This behaviour indicates the presence of **instability** (snap-through type behaviour) in the system.



Wing Morphing : Control Implications

This behaviour creates challenges for pressure-based control:

- Stable pressure control is only possible up to the maximum pressure point.
- Beyond this, the system becomes unstable and curvature can no longer be controlled effectively using pressure alone.

If curvature must still be controlled beyond this range:

- The control variable must directly be curvature (state feedback control).
- This greatly increases system complexity and hardware requirements.

Consequently, pure pressure actuation fails to provide full-range morphing authority.

Wing Morphing : Important Question

This leads to a practical design question:

Can we exploit only the stable regime of pressure control for effective wing morphing?

Specifically:

- Does the stable region provide sufficient geometric change?
- How much aerodynamic benefit is lost by ignoring the unstable region?

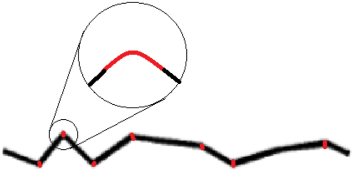
To answer this, aerodynamic performance comparisons are made between:

- Full range morphing (stable + unstable)
- Stable-region-only morphing

2-D Wing Model

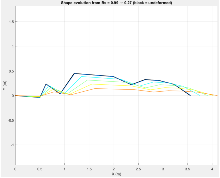
Dragonfly corrugated wings exhibit **spatial variation in material properties** along the cross-section:

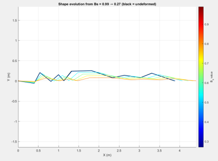
- The **corrugation vertices (folds)** consist of softer, highly deformable material, primarily composed of resilin-rich cuticle.
  - Well-approximated as a **Neo-Hookean material**
  - Typical Young's modulus: $E_j \approx 1 - 10$ MPa (≈ 5 MPa)
- The **straight segments between folds** are stiffer and primarily composed of sclerotized cuticle.
  - Behaves closer to linear elastic material
  - Typical Young's modulus: $E_s \approx 1 - 5$ GPa (≈ 2.5 GPa)

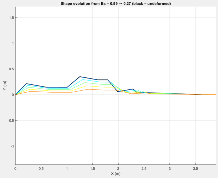


Morphed Structures for Each Spanwise Section

- Morphed configurations generated using the pressure–curvature model.
- Each image corresponds to one spanwise section of the wing.
- Morphing shown from undeformed to maximum deformation state.
- These profiles were later used for CFD simulations to evaluate aerodynamic performance.







Thickness-to-Chord Ratio Variation

The change in geometry due to pressure-induced morphing alters the effective thickness-to-chord ratio of the wing sections. The table below compares the values for the **1st (least morphed)** and **5th (most morphed)** states.

Section Location	t/c (State 1)	t/c (State 5)	% Change
Section 1 (0.3b)	0.125	0.034	$\downarrow$ 72.8%
Section 2 (0.5b)	0.064	0.017	$\downarrow$ 73.4%
Section 3 (0.7b)	0.0961	0.026633	$\downarrow$ 72.3%

- State 1 represents the baseline (minimum morphing).
- State 5 represents the maximum morphing configuration.
- All three sections exhibit a consistent **72–73% reduction in thickness ratio**.
- Such large reduction significantly alters camber, pressure distribution and separation behaviour.

Wing Morphing : CFD Simulation Setup

The script outputs CSV files containing vertex coordinates for each morphed shape.
For CFD analysis:

- Three spanwise sections selected: 0.3l, 0.5l, 0.7l
- Five morphing states per section
- Pressure range: 0.99 $\rightarrow$ 0.27 (covering stable and unstable regions)

Total shapes: **15**
Angles of Attack considered:

$$-10, -5, 0, 5, 10, 15, 20, 22, 24, 26, 30, 35^\circ$$

Total CFD simulations:

$$15 \times 12 = 180$$

Wing Morphing : Automation Pipeline

A fully automated pipeline was developed to streamline the CFD workflow:

1. CSV coordinate files stored for each morphed configuration
2. SolidWorks macro generates CAD geometry automatically
3. Template OpenFOAM case prepared
4. Bash script orchestrates the entire process

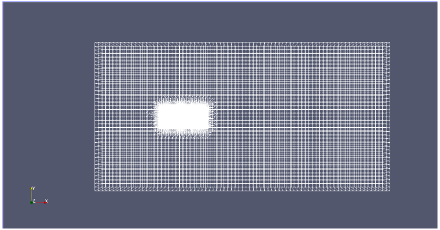
Wing Morphing : CFD Solver Details

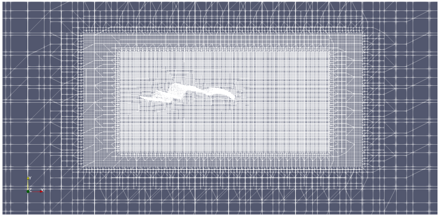
OpenFOAM was chosen over ANSYS due to:

- Superior scripting and automation capabilities
- Easy integration into pipeline

Simulation details:

- Solver: `simpleFoam`
- Steady-state analysis
- Objective: Lift and drag coefficients
- Mesh size: approx. **350,000 nodes per case**





Wing Morphing : Case Definitions

Two primary control strategies were investigated:

Case 1: Shape Control Only

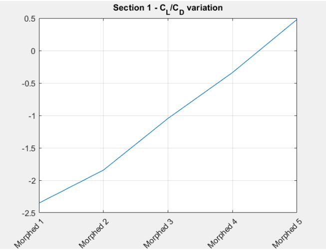
- Cross-sectional shape is controlled
- Angle of attack remains fixed

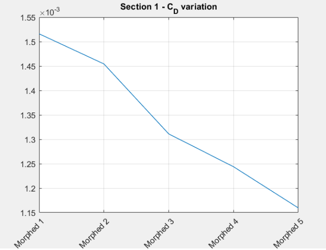
Case 2: Shape + AoA Control

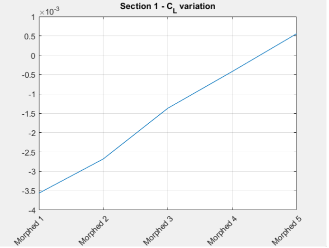
- Both shape and AoA varied
- Provides 2-DOF control space
- Enables exploration of optimal aerodynamic performance regions

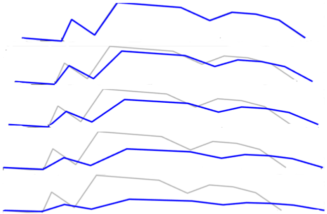
This allows assessment of morphing effectiveness under different control freedoms.

CFD Results : Case 1 – Section 1 (0.3b)

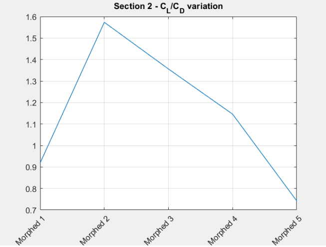


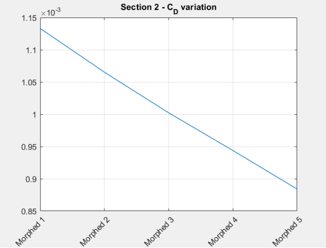


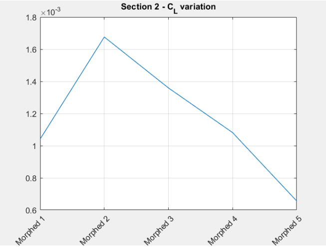


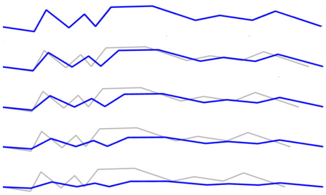


CFD Results : Case 1 – Section 2 (0.5b)

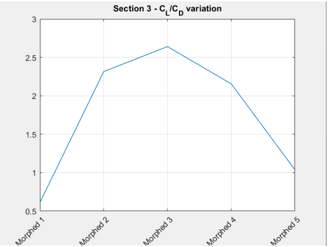


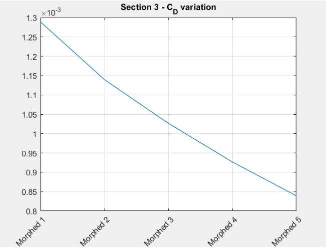


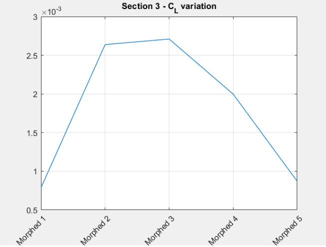


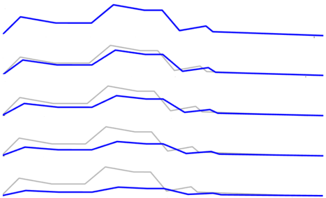


CFD Results : Case 1 – Section 3 (0.7b)

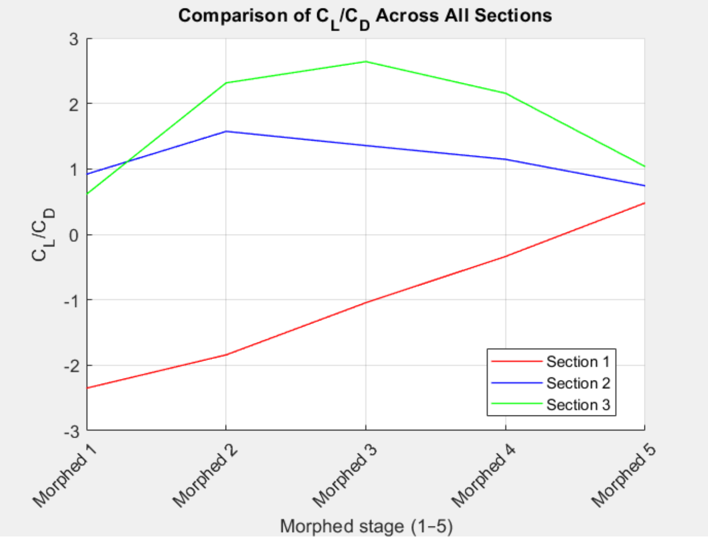




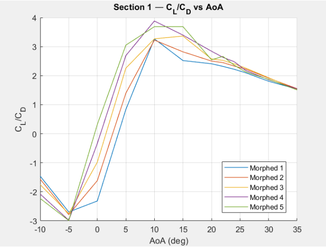


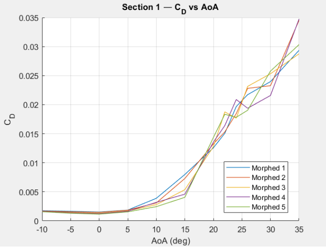


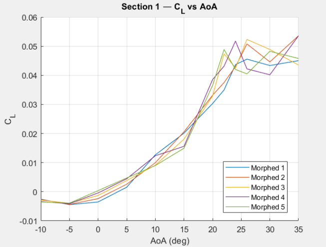
CFD Results : Case 1

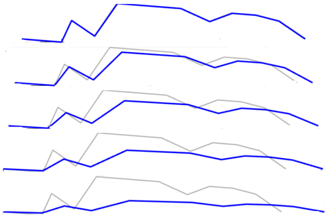


CFD Results : Case 2 – Section 1 (0.3b)

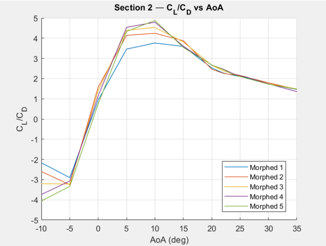


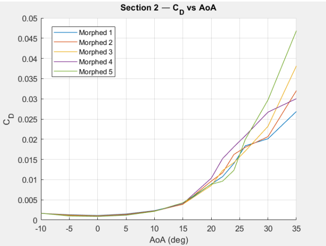


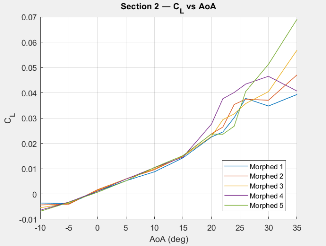


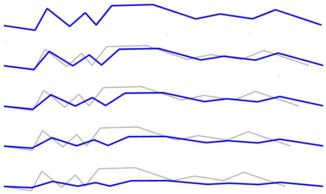


CFD Results : Case 2 – Section 2 (0.5b)

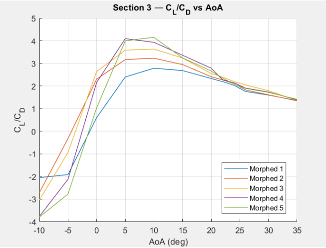


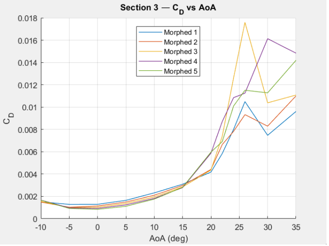


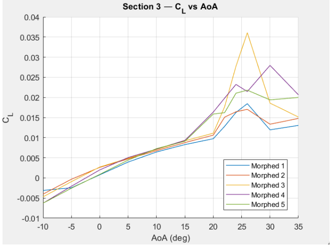


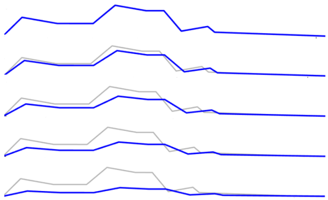


CFD Results : Case 2 – Section 3 (0.7b)









CFD Results : Interpretation

- The maximum percentage improvement in C_L/C_D over the **entire morphing range** is approximately **275%**
- When restricted only to the **stable regime**, this improvement reduces to about maximum of **125%**, but it usually stayes below 100% in this case

The morphed state **State 2** roughly corresponds to the boundary between stable and unstable regions, i.e. the pressure maximum (P_{max}) occurring at:

$$B \approx 0.81$$

Beyond this point, although further deformation is achievable, the associated aerodynamic gains are relatively marginal.

This raises a critical question: How can we achieve larger morphing amplitudes?

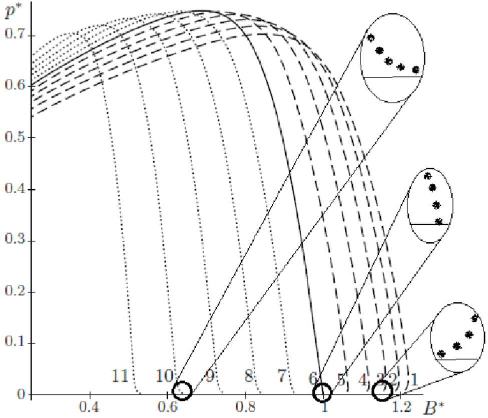
Possible Strategies for Enhanced Morphing

Two potential approaches can be explored:

1. **Direct curvature control (controlling B instead of p)**
   - Difficult to implement at small scale
   - Requires embedded actuators or smart materials
   - Increases wing mass and structural complexity
   - May degrade aerodynamic efficiency
2. **Altering system parameters to reshape the p–B curve**
   - Passive approach (no additional actuators)
   - Can potentially shift instability point
   - Provides higher morphing authority in stable region

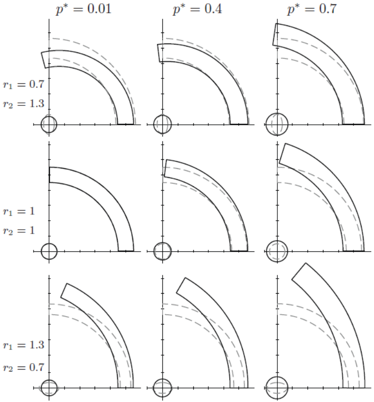
Effect of Tube Cross-Section

- A follow-up study by the same author investigates the influence of **cross-sectional geometry** on the unbending response of pressurised tubes.
- He examined the p vs B behavior for elliptical cross sections
- For p vs B relationship varies differently for horizontal ellipse, circle and vertical ellipse. (solid line represents circular cross section, and curves on its left and right are horizontal and vertical ellipse respectively)



Cross-Section Influence on Morphing Performance

- Elliptical cross-sections exhibit **greater deformation** at lower pressures compared to circular tubes.
- This improves morphing authority within the stable regime.
- However, practical challenges arise:
  - Increased manufacturing complexity
  - Reduced structural robustness
  - Potential durability issues



Final Thoughts

- Dragonfly wing aerodynamics was studied for both 2-D and 3-D
- An attempt was made to find ways for morphing in corrugated wings
- The feasibilty and benefits of the choosen mechanism were studied using literature available and thereafter using CFD data, due to challenges posed in controls due to instability
- Need to find new ways to make it possible
- Moving to elliptical cross section shows some good signs, but need more study around it

Thank you!

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