Aeroelastic Analysis of Highly Flexible Flapping Wings Using an ALE Formulation of Embedded Boundary Method for Turbulent Fluid-Structure Interaction Problems

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Micro Air Vehicles (MAVs) as defined by DARPA

- Dimension ≤ 6 inches
- Weight ≤ 100g
- Endurance ≥ 1 hour
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MAV Applications:
- Reconnaissance
- Surveillance of hazardous places
- Aerial photography etc.

“Over the hill” Reconnaissance

Operations in Dangerous Environments
Micro Air Vehicles (MAVs) as defined by DARPA

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- Endurance $\geq 1$ hour

MAV Applications:

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- Surveillance of hazardous places
- Aerial photography etc.

MAV Requirements:

- Efficient
- Highly maneuverable
- Insensitive to gust
- Hover capable
Micro Air Vehicles

Three types of MAVs

- **Fixed Wing**
  - Simple, fast, and efficient
  - No hover capability
  - Only for outdoor missions

- **Rotary Wing**
  - Hover capable
  - Poor efficiency
  - Low endurance
  - Sensitive to wind gusts

- **Flapping Wing**
  - Bio-inspired
  - Potential solution
  - Hover capable, maneuverable, insensitive to gusts
  - Limited understanding
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Two different forms of flapping in nature

- **Avian Flapping**
  - Flaps in vertical plane
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  - Needs forward velocity

- **Insect Flapping**
  - Flaps in nearly horizontal plane
  - Large changes to wing pitch
  - Hovering flight → Suitable for hover-capable MAVs
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**Common Feature:**

- Wing flexibility
  - Avian wings → Moderately flexible
  - Insect wings → Extremely flexible
Challenges in building flapping-wing MAVs:

- Difficult to mimic kinematics of nature
- Thin, highly flexible wings undergoing large deformations
  - Complex non-linear aeroelastic problem
  - Wide design space involving aerodynamic, kinematic and structural variables
- Time consuming experimental studies
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Solution:
- Computational studies
  - Explore large design space
  - Understand flow features hard to measure with experiments
Past Computational Studies

2D CFD analysis
Tuncer et al. (1999), Young et al. (2007)

3D rigid wing or prescribed motion CFD analysis

FSI simulation using low-order aerodynamic analysis
Liani et al. (2007), Kim et al. (2008), Gopulapati et al. (2013)

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⇒ Difficulty simulating highly flexible wing → Uses Arbitrary Lagrangian Eulerian (ALE) framework
Arbitrary Lagrangian-Eulerian (ALE)

- Popular method for solving FSI problems
- Body-fitted mesh
  - Precisely tracks the structure
  - Free to move arbitrarily inside computational domain

Advantage:
- Relatively simple treatment of material interfaces

Disadvantage:
- Lacks robustness with respect to large deformations
- More sensitive in stretched viscous grids

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Eulerian grid $\Omega_h$

- real node
- ghost node
Advantages:

- Robust to handle any arbitrarily large deformation
Resolve flow features near structure
Viscous flows $\rightarrow$ boundary layer
One solution → refine large portion of grid
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- Very expensive
- Structural deformation $\rightarrow$ **Rigid** + **Deformational** part
- Fluid mesh tracks the rigid component
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- Fluid mesh tracks the rigid component
Objectives

- Main objective is to perform high fidelity non-linear aeroelastic analysis of extremely flexible flapping wings using the ALE-embedded method

- Detailed validation of the simulation with available experimental data
AERO Suite of Codes

**AeroF:**
- Three-dimensional, unstructured, compressible, multi-phase, finite volume based Navier-Stokes solver
- Second- and higher-order spatial discretization
- Convective fluxes based on the Roe, HLLE, or HLLC schemes
- Galerkin centered approximation method for the viscous fluxes
- Second- or higher-order time discretization with DGCLs
- FIVER embedded boundary method
  - On solution of exact, one-dimensional Riemann problems

**AeroS:**
- Parallel linear, nonlinear, comprehensive, solid and structural dynamics finite element code
- Can interact with AeroF for coupled fluid-structure problems

**Peripheral Modules:** Sower, Matcher
Experiments of Wu et al.

- Capran film supported by carbon fiber based spar-batten skeleton
- Different wings tested → named LiBj
  - i → number of composite layers on leading edge
  - j → number of composite layers on battens
  - Root has two composite layers

**Figure**: Flapping wing planform, Wu et al.  
AIAA-2009-2413
Flapping Wing Setup

- Experiments of Wu et al.
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Figure: Flapping wing planform, Wu et al.  AIAA-2009-2413

Flapping Motion

- $35^\circ$ flap angle
- Flapping frequency varies from 5Hz to 40Hz
- Max tip velocity $\approx 11$ m/s ($\text{Mach} \approx 0.03$)
- Max tip Reynolds number $\approx 10,000$
  - Based on root chord
Finite Element Model

- High-fidelity, nonlinear, multi-body dynamics model
- Rigid and flexible shell elements
- Roughly 13,000 degrees of freedom.

Fluid Mesh

- 1.4 million nodes
- 8.5 million tetrahedral elements
Three different wings simulated

- Flexibility $\rightarrow$ L1B1 > L2B1 > L3B1
Comparison with Experiment - Tip Deflection

At 25Hz flapping frequency

Figure: L1B1 wing
Red curve shows tip deflection of rigid wing

Figure: L2B1 wing

Figure: L3B1 wing

Qualitative trends very well predicted
All three wings show lagged response
▶ Larger flexibility → More lag
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![Graphs showing tip deflection for different wings at 25Hz flapping frequency.](image)

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At 25Hz flapping frequency

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Trends well predicted

Best wing

Low frequency $\rightarrow$ L1B1
Mid frequency $\rightarrow$ L2B1
High frequency $\rightarrow$ L3B1

Correlation between inertial loads, wing flexibility and thrust generation

Difference between CFD and experiment

Difficulty modeling glue
Uncertainties in geometry and material properties

Thrust Comparison with Experiment

Equivalent to lift for wing flapping in horizontal plane
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At 25Hz flapping frequency

L2B1 has coherent leading edge vortex, L1B1 does not

Figure : L1B1 wing

Figure : L2B1 wing
A nonlinear aeroelastic validation study of a highly flexible flapping wing is presented using the recently developed ALE formulation of Embedded Boundary Method.

Comparison of predicted structural deformations and aerodynamic thrust with the experimental data show good qualitative agreement.

The quantitative differences are primarily attributed to the uncertainties in the structural model.

Wing flexibility beneficial, but excessive flexibility can be detrimental.
A nonlinear aeroelastic validation study of a highly flexible flapping wing is presented using the recently developed ALE formulation of Embedded Boundary Method.

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