The Numerical Simulation of Flapping Wings at Low Reynolds Numbers

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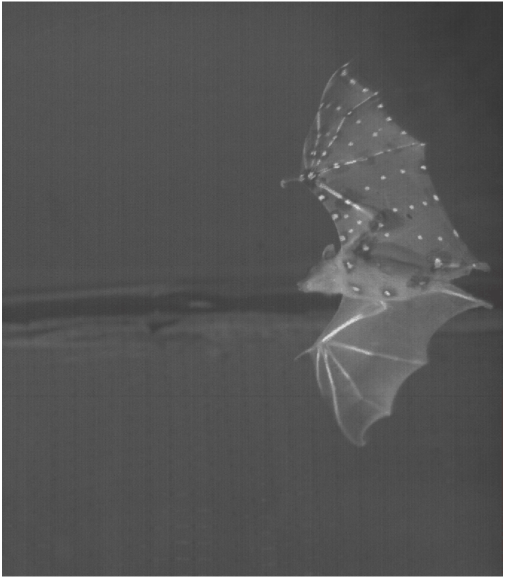
48th AIAA Aerospace Sciences Meeting, Orlando, Florida

January 5, 2010

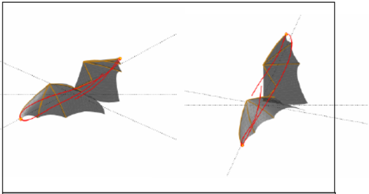
Outline

Bio-Inspiration for MAVs



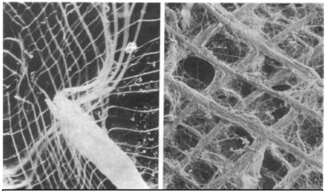
Motivation

- Flapping flight design space is diverse and complex:



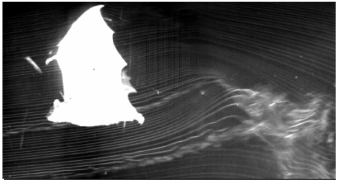
Complex Kinematics

Riskin, Willis et al, 2007, submitted.



Complex Structures

Holbrook & Odland, 1978

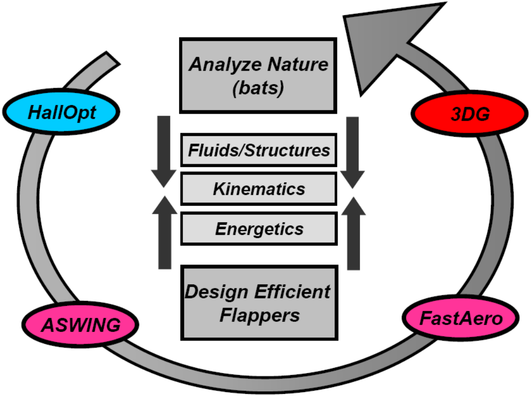


Complex Fluid Dynamics

Challenging Energetics Evaluation

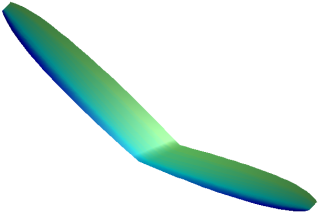
Motivation

- Possible solution: Multi-fidelity methods
  - Reduction in physics fidelity $\longrightarrow$ Potential flow
  - Reduction in mathematical complexity $\longrightarrow$ ROMs

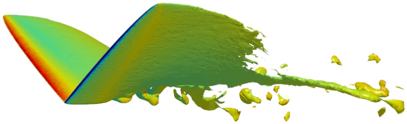


Assessing Limits of Low Fidelity

- Consider a simple analytically prescribed flapping motion
- Compare lower fidelity model (panel method) with higher fidelity simulations (Navier-Stokes)
- Objective: Understand the limits of validity for each approach



FastAero

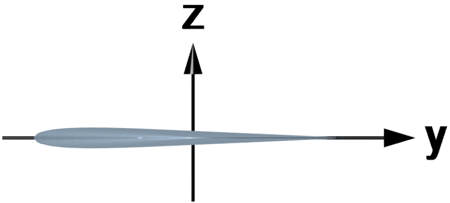


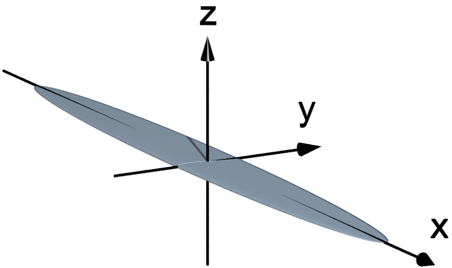
3DG

Outline

Wing Geometry and Flow Properties

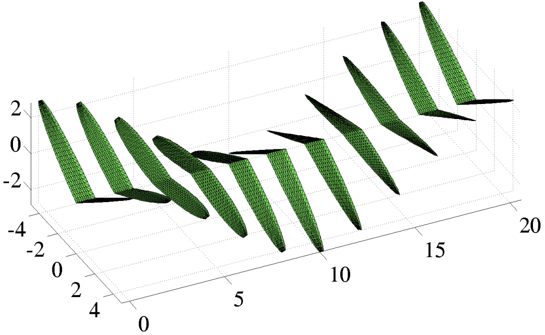
- Elliptical planform, chord at centerline $c = 1$, tip-to-tip span $b = 10$
- HT13 airfoil for the entire wing span
- Maximum wing thickness $t = 0.065$ at the wing centerline
- Mach number 0.1, Reynolds number 2,000
- Four simulation cases, with angles of attack $0°$, $2.5°$, $5°$, and $10°$



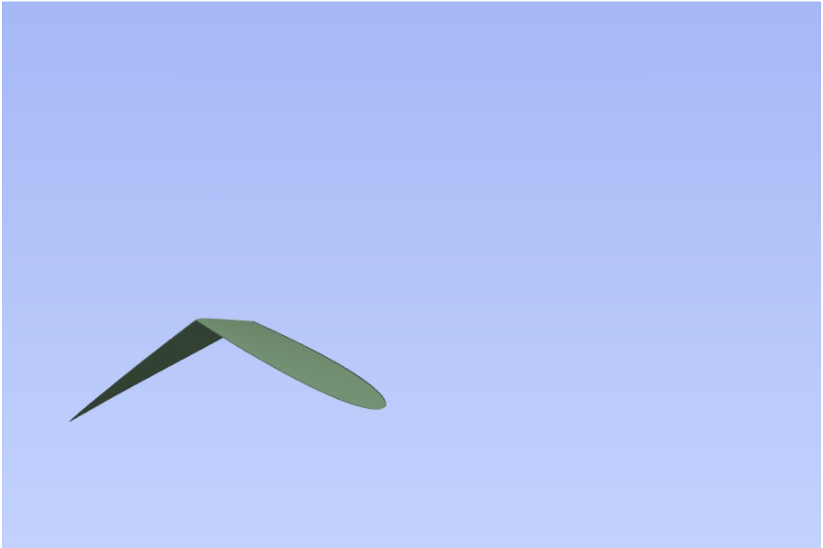


Flapping Motion

- Simple analytical expression for the flapping motion
- Not an optimized flapping strategy, but representative and adequate for comparison of computational models
- Symmetric wing motion with flapping angle $\phi(t) = A_\phi \cos \omega t$ at time t, with amplitude $A_\phi = 30^\circ$ and frequency $\omega = 2\pi/20$
- Also, a wing twist angle $\theta(t) = \frac{\omega X \tan A_\phi}{U + c/2} \sin \omega t$ is prescribed at distance X from the centerline (freestream velocity U, chord length c)



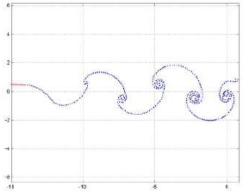
Flapping Motion

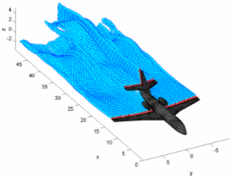


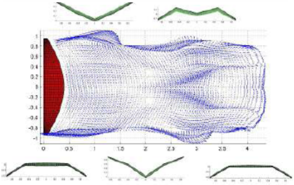
Outline

FastAero

- Panel Method Potential Flow Solution
  - Efficient for large wing motions
  - Requires surface meshes only
- Inviscid, will not be able to model:
  - Flow separation
  - Leading edge vortices
  - Viscous drag
- Implementation Details
  - Linear basis unstructured panel method
  - Unsteady free vortex particle/sheet wakes
  - Accelerated iterative solution (pFFT, FMM)

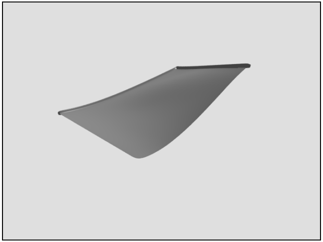




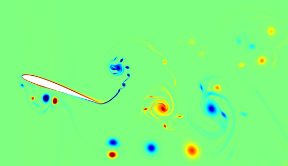


The 3DG Discontinuous Galerkin Solver

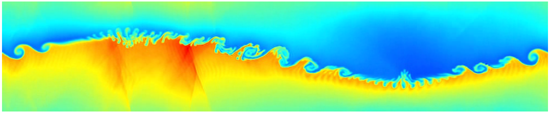
- High-order discretizations on unstructured meshes
- Capable of simulating challenging problems:
    - complex real-world geometries
    - transitional flows, multiple scales
    - moving and deforming domains
    - fluid-structure interactions
- General multiphysics framework applicable to a wide range of challenging problems



Thin Structures



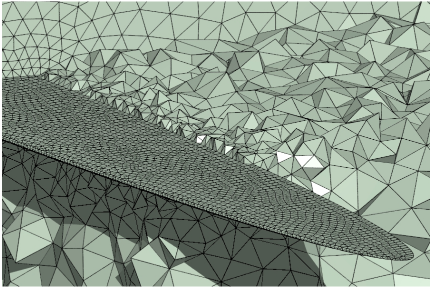
Unsteady Flows

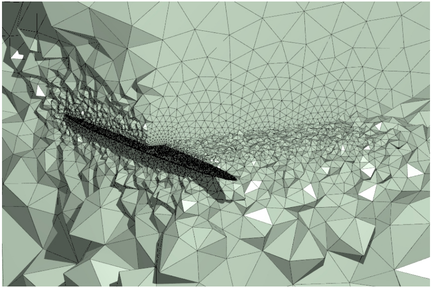


Aeroacoustics

Tetrahedral Mesh

- Surfaces triangulated in parameteric form using the DistMesh mesh generator [Persson '04], and tetrahedral volume mesh generated by a Delaunay refinement code [Peraire '98]
- 30,000 nodes and 160,000 tetrahedra in the half-domain
- Resolution focused around wing and in the wake
- Elements close to wing curved using nonlinear elasticity approch [Persson/Peraire '09]





Discontinuous Galerkin Discretization

- Discretize general system of the form

$$\frac{\partial u}{\partial t} + \nabla \cdot F_i(u) - \nabla \cdot F_v(u, q) = S(u, q)$$

$$q = \nabla u,$$

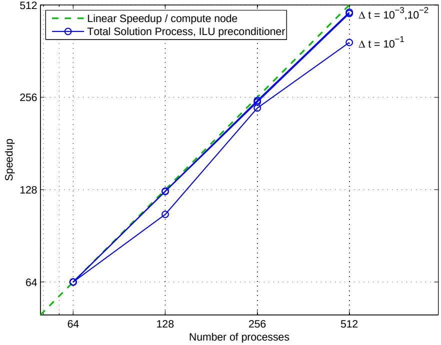
- Nodal basis functions, polynomial degrees $p = 3$, total number of degrees of freedom $\approx$ 19M
- Use Compact Discontinuous Galerkin (CDG) method for viscous fluxes [Peraire '08]
- Space discretization produces large system of ODEs

$$M \frac{dU}{dt} = R(U)$$

- Integrate in time with L-stable 3rd order accurate DIRK scheme

Parallel Newton-Krylov Solvers

- Implicit solvers required because of CFL restrictions from viscous effects, unstructured meshes, low Mach numbers, etc
- Storage of Jacobian $J = \partial R / \partial U$ requires about 55GB of memory
- Use block-ILU(0) preconditioner with MDF ordering [Persson/Peraire, ’08]
- Parallelize by domain decomposition and partition-wise ILU preconditioner
- Close to perfect speedup for time accurate simulations



Arbitrary Lagrangian-Eulerian (ALE) Formulation

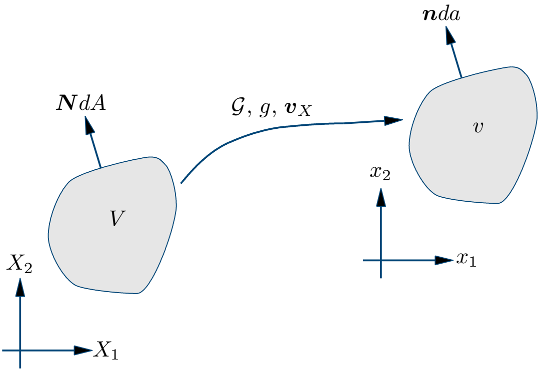
- Use mapping-based ALE formulation for the moving domain [Visbal/Gaitonde '02, Persson/Bonet/Peraire '08]
- Map from reference domain V to physical deformable domain $v(t)$
- Introduce the *mapping deformation gradient* $\boldsymbol{G}$ and the *mapping velocity* $\boldsymbol{v}_X$ as

$$\boldsymbol{G} = \boldsymbol{\nabla}_X \boldsymbol{G}$$

$$\boldsymbol{v}_X = \left.\frac{\partial \boldsymbol{G}}{\partial t}\right|_X$$

and set $g = \det(\boldsymbol{G})$

- Transform equations to account for the motion



Mapping Function

- Need analytical expression that deforms the wing according to the angles ϕ, θ, but extends smoothly to the entire domain
- Simple approach: Two shear motions + Scaling

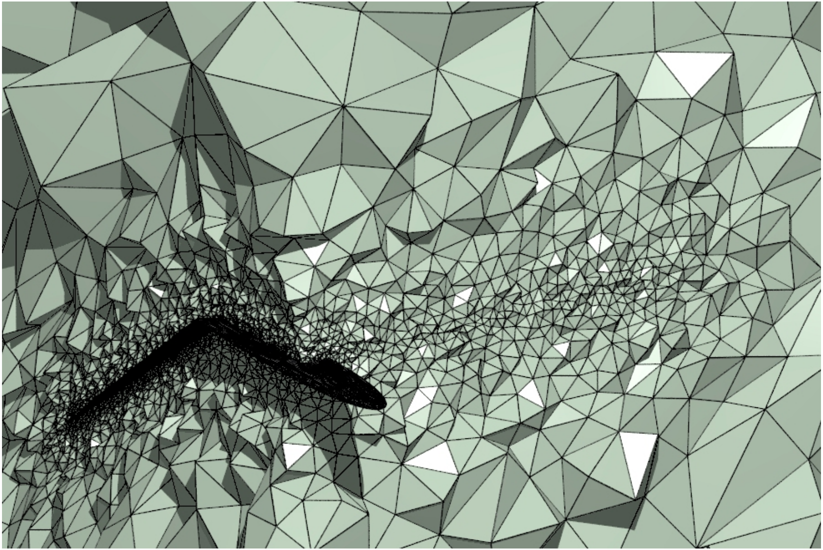
$$x(X,t) = \begin{bmatrix} X\cos\phi \\ Y \\ X\tan\phi + Y\tan\theta + Z\sec\phi, \end{bmatrix}$$

- Volume-preserving deformation gradient ($\det(G) = 1$):

$$G = \frac{\partial x}{\partial X} = \begin{bmatrix} \cos\phi & 0 & 0 \\ 0 & 1 & 0 \\ G_{31} & G_{32} & \sec\phi. \end{bmatrix}$$

- Grid velocity $\partial x / \partial X$ also found by analytical differentiation

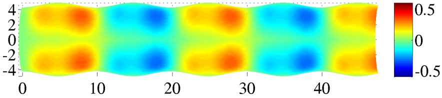
Mapping Function



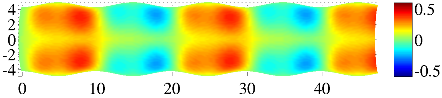
Outline

Potential Flow – Wake Structure

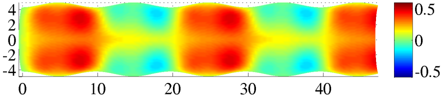
- Momentum footprint and the corresponding wake structure
- A moderately strong tip vortex, coupled with starting and stopping vortices during each cycle
- Increasing the AoA appears to increase the mean circulation



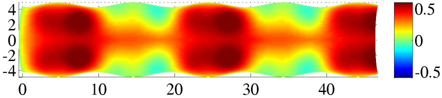
AoA $\alpha = 0^\circ$



AoA $\alpha = 2.5^\circ$



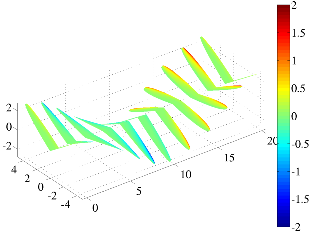
AoA $\alpha = 5^\circ$



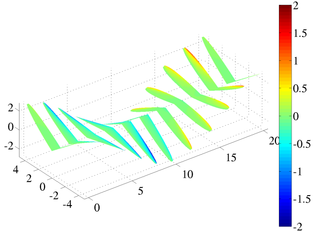
AoA $\alpha = 10^\circ$

Potential Flow – Surface Pressure Differentials

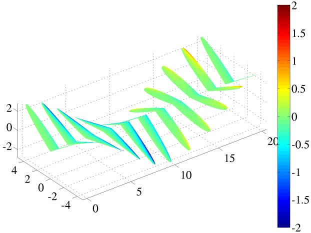
- Adverse gradients indicate regions of likely separation



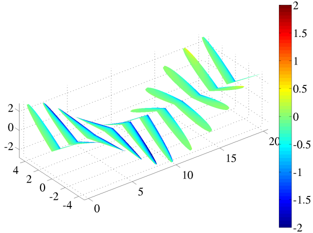
AoA $\alpha = 0°$



AoA $\alpha = 2.5°$



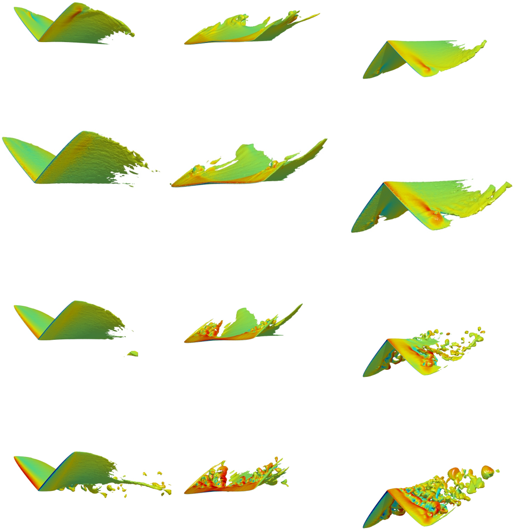
AoA $\alpha = 5°$



AoA $\alpha = 10°$

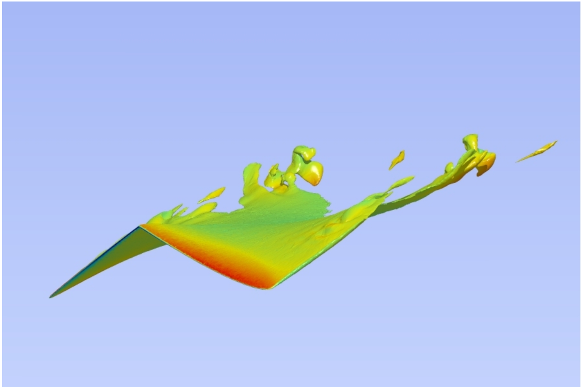
Navier-Stokes Simulation – Results

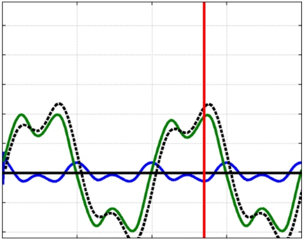
- Reynolds number $\mathrm{Re} = 2,000$
- Angle of attack $\alpha = 0$, 2.5, 5, and 10 (top to bottom)
- Visualization by Mach number (color) on isosurface of entropy
- 4th order in space, 3rd order in time, fully implicit solver



Navier-Stokes Simulation – AoA $\alpha = 0^\circ$

- The flow stays attached inboard
- Leading edge vortices are shed at the top and bottom

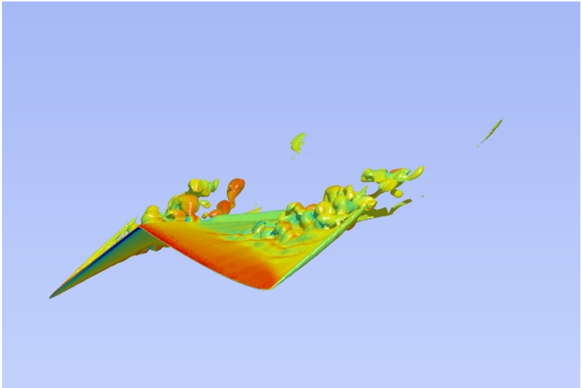


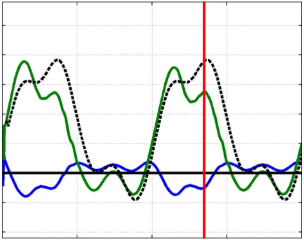


N-S lift (green), N-S drag (blue), Panel lift (dashed)

Navier-Stokes Simulation – AoA $\alpha = 5^\circ$

- Significant shedding through last half of downstroke

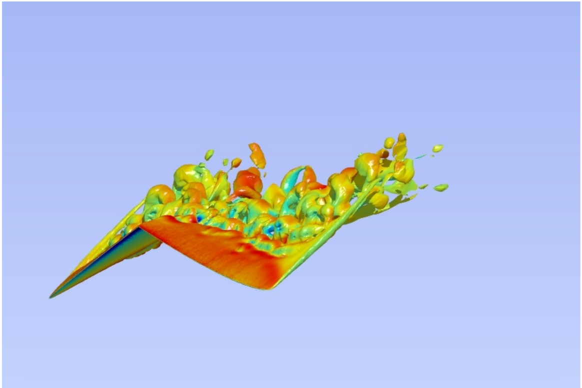


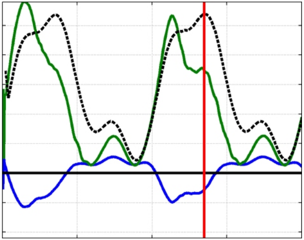


N-S lift (green), N-S drag (blue), Panel lift (dashed)

Navier-Stokes Simulation – AoA $\alpha = 10^\circ$

- Separation during most of the downstroke

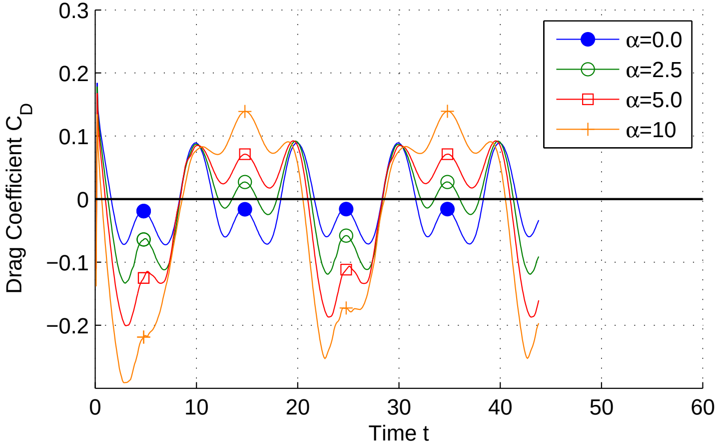




N-S lift (green), N-S drag (blue), Panel lift (dashed)

Drag Coefficients

- Drag forces predicted by the Navier-Stokes simulations
- Viscous corrections could be applied to panel code as well



Conclusions and Summary

- Biologically inspired flight design space is large $\longrightarrow$ multi-fidelity solution approaches
- We examined an off-design flapping wing at several different incidences
- Lower fidelity potential flow approaches show promise for minimal flow separation and vortex shedding cases
- Viscous corrections or higher fidelity methods are critical for assessing more aggressive flows