Modeling Rigid Flapping Wing Flight using OVERFLOW

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Introduction

Nature has provided us with highly maneuverable insects and birds inspiring the development of micro air vehicles (MAV). MAV design is an emerging area in aeronautics that requires accurate solutions of flapping wing geometries. The difficulty of obtaining the unsteady solutions of flapping wing flight is compounded by the combined low-Mach and low-Reynolds number flow regime. We employ a NASA flow solver for both two and three dimensional cases in search of both accurate and efficient flow solutions.

Motivation

Design of a flapping wing configuration will ultimately rely on optimization of both the motion and geometry of the vehicle. The unsteady and complex nature of the flow fields associated with flapping wing flight quickly make solutions cost prohibitive. A full scale optimization requires the solution of many flapping cycles per objective function evaluation. Thus, our goal is to ascertain an automated process for delivering accurate and efficient solutions of flapping wing geometries with the intention of reducing the computational cost of a design optimization.

Technical Approach

NASA OVERFLOW Solver

- Highly parallelized Navier-Stokes finite-difference solver
- Overset framework
- Implicit second-order dual time-stepping algorithm
- Third-order spatial accuracy (higher-order available)
- Structured curvilinear body conforming grid embedded in a set of automatically-generated Cartesian off-body grids
- X-rays perform dynamic hole cutting[1]
- DCF provides interpolation across grid interfaces[2]

Grid proximity adaption was used to improve efficiency. Solution adaption will be used in the future to improve accuracy. A more detailed explanation of Overflow can be found in the paper by Nichols, Tramel and Buning.[3]

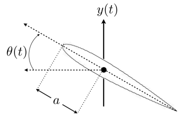
A variety of grid and time step parameters were investigated for the two-dimensional case including the physical time step, number of sub-iterations per time step, level-one grid spacing and domain size and location of the airfoil within the domain.

Two Dimensional Pitching & Plunging NACA 0012 Airfoil

Kinematics

The kinematics of the pitching a plunging airfoil are described by the equations for plunge height, *y(t)*, and rotation angle, *ϑ(t)*.

$$y(t) = -h\cos(kt)$$
$$\theta(t) = -\alpha\cos(kt + \phi)$$

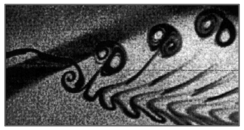


The parameters describing the kinematics are the reduced frequency, *k*, the nondimensional plunge amplitude, *h*, the pitch amplitude, *α*, the pitch-plunge phase shift, *ϕ*, and the pitch-axis, *a*.

Verification

Overflow results compared with those found in the literature. Solution shown for the deflecting vortex case of *k* = 12.3 and *h* = 0.12 and the experimental results of Jones, Dohring and Platzer.[4]

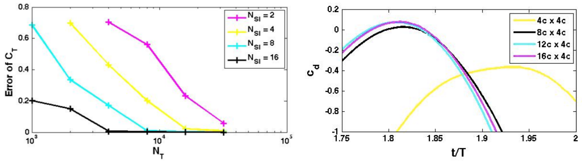
OVERFLOW



Experiment

Towards Efficiency

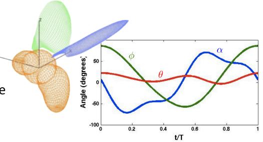
A major effort focused on isolating the minimum time step and grid that can accurately and efficiently model the rigid pitching and plunging airfoil. The figure on the left demonstrates error in mean thrust coefficient (C_T) as a function of total time steps per flapping cycle (N_T) for different values of implicit sub-iterations (N_{SI}). The figure on the right highlights the dependence of the drag coefficient on the size of the level one grid (D_x x D_y) in multiples of chord length, *c*.



Preliminary Three Dimensional Flapping Fruit Fly

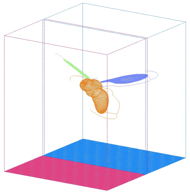
Geometry & Kinematics (from Liu & Maeda, Chiba University, Japan)

The preliminary geometry consists of three near-body grids representing the body and two wings of the fly. Flapping includes three time-dependent rotations represented by a 4-coefficient Fourier series reconstruction based on observed flapping of the fruit fly. The initial surface grid is 45x45 points on each wing and 45x47 points on the body. These grids will be modified to increase resolution.

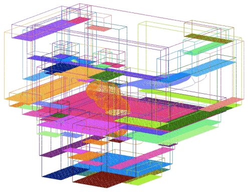


Grid Adaption For Efficiency

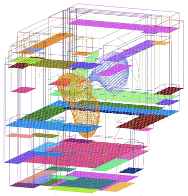
Proximity adaption was employed to automatically regenerate the level-one grids as the solution advanced in time. This provided significant cost savings as the region encompassing the fruit fly geometry varies greatly through its flapping cycle.



No Adaption
6.04 million grid-points



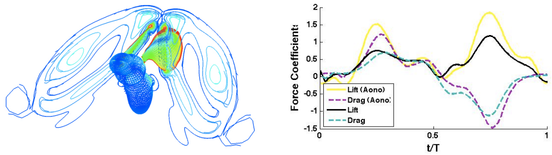
Wings Fully Extended with Adaption
2.60 million grid-points



Wings Collapsed with Adaption
1.79 million grid-points

Results

An image of the flow field and a comparison of computed loads from Aono et al[5].



References

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[6] Leffell, J., and Pulliam, T. H. 2011. "Grid and Time Step Requirements to Accurately and Efficiently Resolve Flow around a NACA 0012 Airfoil," to be presented at the *49th Aerospace Sciences Meeting*, January 4-7, 2011.

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Conclusions and Future Work

Preliminary results for the three-dimensional case are encouraging but significant modifications will be made to the grid topology. The number of near-body grids will be increased to better resolve the flow in high-gradient regions such as the wing edges. Additionally, the OVERFLOW low-Mach preconditioner will be studied to address some high frequency noise in the extremely low Mach cases (M_∞= 0.0074 is the maximum wing tip velocity in the fruit fly flapping cycle).

Many temporal and spatial parameters were explored in the two-dimensional case but only limited results are displayed here. Please see the full paper[6] (to be delivered January 2011) for more details. Insights gained in the 2D studies will aid the 3D work where computational costs escalate more rapidly.