HIGH FIDELITY OPTIMIZATION OF FLAPPING AIRFOILS AND WINGS

Matt Culbreth
Stanford University
Advisor: Antony Jameson
INTRODUCTION

• Flapping wings have gained a lot of attention in the last few years

• Flapping wings are interesting from both a scientific and engineering perspective

• From nature it is obvious that flapping wings can be very effective, but it is far from clear how to make use of them
A big open problem in flapping wing aerodynamics is understanding the link between wing kinematics and performance.

There are many potential degrees of freedom - complex motion in time, wing deformation.

Different objectives - forward flight, hovering, maneuvering.

Flow physics is highly non-linear.
GOALS

• Our goal is to find flapping wing motions that result in efficient flight performance

• Establish trade-offs between complexity of parameterization and achievable efficiency

• Investigate mechanisms that lead to efficient flight

• Determine limits of efficiency

• We do this by coupling high-fidelity CFD tools with numerical optimization
SYSTEM OVERVIEW

Optimization Algorithm

Wrapper

Solver

Parameters
Objective Function Value

Input File
Motion
Deformation

Time History of Forces
2D OPTIMIZATION

• Maximize the propulsive efficiency of a pitching and plunging NACA0012 airfoil at $\text{Re}=1,850$ and $\text{M}=0.2$, 1024x128 mesh, 5 cycles

• In 2D we parameterize a pitching and plunging airfoil
  \[ \alpha(t) = \alpha_0 + \alpha \cos(2\pi ft + \phi) \]
  \[ h(t) = h \cos(2\pi ft) \]

• Four Parameters: Frequency, Pitch Amplitude, Plunge Amplitude and Phase (initial angle of attack is always zero)
# 2D Optimization

<table>
<thead>
<tr>
<th>Case</th>
<th>Freq.</th>
<th>$\alpha$</th>
<th>$h$</th>
<th>$\phi$</th>
<th>$\eta_m$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plunging</td>
<td>2.63 Hz</td>
<td>-</td>
<td>0.252</td>
<td>-</td>
<td>12.1%</td>
</tr>
<tr>
<td>Pitch/Plunge</td>
<td>4.61 Hz</td>
<td>19.78°</td>
<td>0.212</td>
<td>67.03°</td>
<td>31.4%</td>
</tr>
</tbody>
</table>
VISUALIZATION
3D OPTIMIZATION

- Maximize the propulsive efficiency of a flapping rectangular plate
- Aspect Ratio=8, NACA0012 section, Re=2,000, M=0.2, 256x64x64, 2 cycles then 5 cycles
- In 3D we parameterize the root dihedral angle and the spanwise twist distribution

$$\theta_k(t) = \theta_k \cos(2\pi ft + \phi_k)$$

$$\alpha_l(t) = \alpha_l \cos(2\pi ft + \psi_l)$$
MESH MOTION
MESH MOTION
## 3D OPTIMIZATION

<table>
<thead>
<tr>
<th>Control Points</th>
<th>Freq.</th>
<th>θ</th>
<th>Cumulative α</th>
<th>ηm</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>3.63 Hz</td>
<td>6.53°</td>
<td>-</td>
<td>9.60%</td>
</tr>
<tr>
<td>1</td>
<td>0.64 Hz</td>
<td>46.9°</td>
<td>62.5°</td>
<td>46.7%</td>
</tr>
<tr>
<td>2</td>
<td>0.78 Hz</td>
<td>47.1°</td>
<td>58.4°</td>
<td>49.5%</td>
</tr>
<tr>
<td>4</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>No Improvement</td>
</tr>
</tbody>
</table>
Linear Twist
Non-Linear Twist
LEADING EDGE SEPARATION
SUMMARY OF RESULTS

- Optimization can effectively improve the propulsive efficiency of a suboptimal design

- Twisting/pitching motion significantly improves achievable propulsive efficiency

- Motions that optimize propulsive efficiency appear to be on the verge of leading edge separation

- Leading edge separation appears to be a limiting factor in achievable propulsive efficiency
FUTURE WORK

• Constrained optimization - minimize power for specified $C_L$ and $C_D$

• Additional parameterizations - non-linear dihedral distribution, planform variation, additional sinusoidal modes

• Accelerate optimization - multi-fidelity simulations, parallelize across gradient evaluations, stochastic gradients approximation
QUESTIONS?