Micromechanical Flying Insect

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Key Requirements for MFI

- Lift Generation Mechanism - Wing Design & Actuation
- Fast & Robust Feedback Mechanism for Flight Stability and Control
- Power
Outline

- Elements of Wing Motion
- Piezoelectric Actuation
- Generation of Wing Motion
- Actuator/Wing Design & Fabrication
- Testing: aerodynamics, power dissipation, mechanics
- Open Issues
- Schedule
Elements of Wing Motion

Non-Steady State Aerodynamics

**Hover Fly:** $\theta = 60^\circ$

**Most Insects:** $\theta = 120^\circ$

Front View: Angular Stroke

Side View: Angle of Attack

**Most Insects:**

$30^\circ < \phi < 45^\circ$

Other Key Feature

- Elastic Energy Storage in Muscle to Reduce Inertial Power, i.e. to accelerate the wings

**Perspective View:**

**Phase Lag**

*Typical of Hover Fly*
Flying Squid: Pulsating Wing Motion for Low Reynolds Number Flight

Wing Motion, $\delta$

Wing Deflection, $\delta$

Wing Motion

$m \equiv 4\rho bw\ell + \rho bw^2$

$\phi = \frac{\ell}{L}$

Time

$\tau_{up}$

$\tau_{down}$
Summary of Wing Motion

Three Main Types

• **Fruit Fly and Most Insects:** High Asymmetry, High Angular Stroke (120°), High Angle of Attack (30-45°), Twisting Motion

• **Hover Fly:** Symmetric Motion, Low Angular Stroke (60°), High Angle of Attack (45°), Intra-wing Phase Lag

• **Pulsating Wing Motion:** Asymmetric Motion, Low Angular Stroke, Zero Angle of Attack
Piezoelectric Actuation

Wing Tip Deflection
\[ \delta = 6d_{31}\left(\frac{L}{H}\right)^2 V \]

Angular Stroke
\[ \tan\left(\frac{\theta}{2}\right) = \frac{3d_{31}LV}{H^2} \]

Resonant Frequency
\[ f_o = 0.16\left(\frac{H}{L^2}\right)\sqrt{\frac{E}{\rho}} \]
## Piezoelectric Materials & Performance

Choose Length = 2 mm & Thickness = 2 µm

<table>
<thead>
<tr>
<th>Material</th>
<th>Piezo Coefficient, $d_{31}$ (pC/N) or (pm/V)</th>
<th>Density, $\rho$ (g/cm$^3$)</th>
<th>Elastic Modulus, $E$ (GN/m$^2$)</th>
<th>Dielectric Constant, $\varepsilon/\varepsilon_0$</th>
<th>Electromech. Coupling Coeff., $k_{31}$ (%)</th>
<th>$\frac{k_{31}}{\rho}$ (cm$^3$/g)</th>
<th>$\delta V$ (mm/V)</th>
<th>$\theta$ (deg/V)</th>
<th>$f_o$ (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PVDF$^a$ ($\beta$-phase)</td>
<td>$d_{31} = 20-30$</td>
<td>1.8</td>
<td>1-3</td>
<td>10-15</td>
<td>11</td>
<td>6.1</td>
<td>0.15</td>
<td>4.3</td>
<td>85</td>
</tr>
<tr>
<td></td>
<td>$d_{32} = 2-3$</td>
<td></td>
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<tr>
<td></td>
<td>$d_{33} = -30$</td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>PVDF ($\delta$-phase)</td>
<td>$d_{31} = 10-17$</td>
<td></td>
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<td></td>
<td>$d_{32} = 2-3$</td>
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<tr>
<td></td>
<td>$d_{33} = 10-15$</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>VF$_2^-$ trifluoroethylene copolymers</td>
<td>$d_{31} = 15-30$</td>
<td>1.9</td>
<td>1</td>
<td>15-20</td>
<td>20</td>
<td>10.5</td>
<td>0.132</td>
<td>3.8</td>
<td>58</td>
</tr>
<tr>
<td>Poly(vinyl fluoride)</td>
<td>$d_{31} = 1$</td>
<td>1.4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Poly(vinyl chloride)</td>
<td>$d_{31} = 1$</td>
<td>1.5</td>
<td>4</td>
<td>3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lead zirconate titanate (PZT)</td>
<td>$d_{31} = -100-300$</td>
<td>7.5</td>
<td>80</td>
<td>1200</td>
<td>30</td>
<td>4.0</td>
<td>1.2</td>
<td>33</td>
<td>263</td>
</tr>
<tr>
<td>Barium titanate</td>
<td>$d_{31} = -80$</td>
<td>5.7</td>
<td>110</td>
<td>1700</td>
<td>21</td>
<td>3.7</td>
<td>0.5</td>
<td>13.7</td>
<td>354</td>
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<tr>
<td>Quartz</td>
<td>$d_{31} = -2$</td>
<td>2.7</td>
<td>80</td>
<td>5</td>
<td>10</td>
<td>3.7</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

$^a$Poly(vinylidene fluoride)

\[ k_{31} = d_{31} \sqrt{\frac{E}{\varepsilon}} \]
Generation of Hover Fly Wing Motion

Characteristics:
\[ \theta = 60^\circ \]
\[ \phi = 45^\circ \]
Phase Lag Control
Elastic Energy Storage

Emulation of Elastic Storage by Resonance Excitation

\[ \tau = 1/f_o \]

Applied Voltage

Power

Phase Lag Controls

Electrode 1

Power Electrode

Elastic Energy Storage

Phase Lag Control Electrodes

Piezoelectric Bimorph
Generation of Fruit Fly Wing Motion

**Elastomer Lever**

- Top View
  - Wing bonded to elastomer membrane
  - Pivot Point
  - Rigid Frame
  - Piezo Cantilever 1
  - Elastomer Membrane
  - Rigid Hexsil
  - Wing

- Front View
  - Wing attack angle controlled by relative positions of cantilevers 1 and 2

- Side View
  - Characteristics
    - $\theta = 120^\circ$
    - $\phi = 30-45^\circ$
    - Asymmetric Motion
    - Elastic Energy Storage

**Wing attack angle controlled by relative positions of cantilevers 1 and 2**
Generation of Pulsating Motion

Characteristics
- Asymmetric Motion
- Low Angular Stroke
- Zero Angle of Attack

Front View

Single element unimorph/bimorph actuation

Applied Voltage vs. Time

Top View

Elastomer Wings

Piezoactuator
Actuator Design

- **Piezoelectric Materials:**
  PZT, PVDF, AlN etc.

- **Materials Issues:**
  Piezoelectric Coefficient, Power Dissipation,
  Piezoelectric Hysteresis, Ease of Fabrication

- **Actuator Designs (Hover Fly, Fruit Fly, Squid):**
  Thickness, Length, Width, Shape, Electrode Shape
  Deflection/Angular Stroke, Mechanical Rigidity,
  Resonant Frequency
Fabrication

- Fabrication of Fully Piezoelectric Wings (Hover Fly, Squid)
  Length: 50 µm to 5 mm to enable scaling studies
  Multiple electrodes for controlling wing motion

- Fabrication of Partially Piezoelectric Wing (Squid)
  Integrating piezoelectric actuators with elastomers
  Length: 50 µm to 5 mm to enable scaling studies

- Fabrication of Piezoelectric Actuator with Elastomer Lever and Hexsil Wings (Fruit Fly)
  Integrating piezoelectric actuators with elastomers
  Integrating elastomer with Hexsil wing
  Length: 1-5 mm
Testing

Static Measurements
• Static actuator deflection
• Mechanical force generation

Dynamic Measurements (as a function of frequency)
• Actuator wing deflection on and off resonance
• Power dissipation in vacuum: material dissipation
• Power dissipation in fluid: viscous dissipation

Aerodynamic Force Measurements
• Lift and Thrust Under Tethered Flight
• Flow Visualization
  Variables: wing size, angular stroke, frequency, angle of attack, phase lag
Aerodynamic Force Measurements
+
Power Dissipation Measurements

Feasibility of Autonomous MFI Flight

Design of MFI (could be more than 1)
Integration of
• Actuator System
• Wing Design
• Power Source
• Flight Control Strategy
Open Issues

• Piezoelectric actuator performance under large deflections is not well known

• Hysteresis and power dissipation in materials is not well understood

• Interaction of piezoelectric, Hexsil, or elastomer wings with fluid forces and the generation of aerodynamic forces is not well understood
Schedule

Piezoelectric Materials Evaluation: 1 month

Piezoelectric actuator design for wing or elastomer lever: 2-3 months

Fabrication: 9-10 months

Testing: 9-10 months

If feasibility is demonstrated

MFI Design 6 months
Appendix

Fluid Forces:

- **Inertia**: \( \rho \left( \frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u} \right) \)
- **Viscous**: \( \mu \nabla^2 \mathbf{u} \)
- **Pressure**: \( \nabla p \)
- **Buoyancy**: \( g \Delta \rho \)

Balance of these forces produces the Navier-Stokes equation.

Reynolds Number: \( \text{Re} = \frac{\text{Inertia}}{\text{Viscous}} = \frac{\rho UL}{\mu} \)

Low Reynolds number flows: \( \text{Re} < 1 \quad \nabla p \approx \mu \nabla^2 \mathbf{u} \)

\( \rho \): density  
\( \mu \): viscosity  
\( p \): pressure  
\( u \): velocity  
\( U \): free stream velocity  
\( g \): gravity
Re < 5
Unseparated symmetric flow, a.k.a. Stokes flow

5-10 < Re < 40
Pair of fixed vortices in the wake

40 < Re < 150
Laminar vortex street

150 < Re < 3x10^5
Boundary layer is laminar up to separation point, vortex street is turbulent

3x10^5 < Re < 3x10^6
Laminar boundary layer becomes turbulent before separation. Vortex street is highly disorganized.

3x10^6 < Re
Turbulent vortex street, but narrower than laminar case

Re = 1.1
Re = 170
Sphere

Drag Coeff: \( C_D = \frac{F}{\frac{1}{2} \rho U^2 \pi D^2} \)

Stokes solution: \( C_D = \frac{24}{Re} = \frac{24}{\rho UD/\mu} \)

Drag Force: \( F = 3\pi \mu UD \)

Infinite Cylinder

Drag Coeff: \( C_D = \frac{F/L}{\frac{1}{2} \rho U^2 D} \)

No Analytical Solution
\( C_D \approx 1 + \frac{10}{Re^{2/3}} \)

Drag Force: \( F \approx 5\mu UL \left( \frac{\rho UD}{\mu} \right)^{1/3} \)
Flying Squid: Pulsating Wing Motion for Low Reynolds Number Flight

Wing Deflection, \( \delta \)

Wing Motion

\[ m \equiv 4\rho bw\ell + \rho bw^2 \]

\[ \phi = \frac{\ell}{L} \]
Analysis

Assumption: \[ F \approx 5\mu UL \left( \frac{\rho UD}{\mu} \right)^{\frac{1}{3}} \approx C\mu UL \]

Force Balance: \[ m \frac{d^2 h}{dt^2} = \frac{\phi}{\tau_v} \frac{d\delta}{dt} - g \]

Viscous Time Scale \[ \tau_v = \frac{m}{4C\mu L} \]

Assumed Wing Motion

\[ \delta = \delta_f \exp \left( -\frac{t}{\tau_u} \right) \left[ 1 - \exp \left( -\frac{t}{\tau_d} \right) \right] \]

\[ \alpha = \frac{\tau_d}{\tau_v} \quad \beta = \frac{\tau_u}{\tau_v} \]

\( \tau_d < \tau_u \quad \beta > \alpha \)
Solution

\[ \frac{h(t_f)}{\phi \delta_f} = \psi \left[ 1 - e^{-\beta^2/(\beta-\alpha)} - \frac{\beta^2}{(\beta-\alpha)} \right] + \frac{(\beta - \alpha)}{(\beta - 1)(\beta - \alpha)} \left[ 1 - e^{-\beta^2/(\beta-\alpha)} \right] - \frac{\alpha}{(1 - \alpha)} \left[ 1 - e^{-\beta^2/\alpha (\beta-\alpha)} \right] - \frac{\beta}{(\beta - 1)} \left[ 1 - e^{-\beta/(\beta-\alpha)} \right] \]

\[ \psi = \frac{g \tau_v^2}{\phi \delta_f} \]

If you drop a mass at \( t = 0 \), then the velocity increases as

\[ U = g \tau_v \left( 1 - e^{-t/\tau_v} \right) \]

where \( g \tau_v \) is the terminal velocity.

If \( h(t_f) > 0 \)  \( \rightarrow \psi < \frac{\beta}{(\beta - 1)} \left[ \frac{e^{-1} - e^{-\beta}}{\beta + e^{-\beta} - 1} \right] = \psi_c \]

\[ \delta_f > \frac{g \tau_v^2}{\phi \psi_c} = \frac{g}{\phi \psi_c} \left( \frac{m}{4C \mu L} \right)^2 \]

Higher viscosity \( \rightarrow \) lower required wing deflection

Notes:

- If \( \alpha = \beta \), then \( h(t_f) < 0 \) for all conditions.
- To consider buoyancy effects, replace \( g \) by \( (\Delta \rho / \rho)g \).
Average Viscous Power Dissipation
\[ \langle P \rangle = \frac{1}{(\tau_d + \tau_u)} \int_0^{\tau_d + \tau_u} 4C\mu L \left( \frac{d\delta}{dt} \right)^2 dt \]

\[ \langle P \rangle = 4C\mu L \frac{\delta_f^2}{\tau_d \tau_u} \]

Peak Power:
\[ P_{max} = 4C\mu L \left( \frac{\delta_f}{\tau_d} \right)^2 \]
## Some Numbers

<table>
<thead>
<tr>
<th></th>
<th>In Air</th>
<th>In Air</th>
<th>In Water</th>
</tr>
</thead>
<tbody>
<tr>
<td>MFD Length, L</td>
<td>1 mm</td>
<td>100 µm</td>
<td>1 mm</td>
</tr>
<tr>
<td>Wing Span, l (ϕ = l/L)</td>
<td>0.8 mm</td>
<td>80 µm</td>
<td>0.8 mm</td>
</tr>
<tr>
<td>Wing Width, w=2(L-l)</td>
<td>0.4 mm</td>
<td>40 µm</td>
<td>0.4 mm</td>
</tr>
<tr>
<td>Wing Thickness, b</td>
<td>1 µm</td>
<td>1 µm</td>
<td>1 µm</td>
</tr>
<tr>
<td>MFD Density, ρ</td>
<td>2400 kg/m³</td>
<td>2400 kg/m³</td>
<td>2400 kg/m³</td>
</tr>
<tr>
<td>MFD Mass, m</td>
<td>3.5 x 10⁻⁹ kg</td>
<td>3.5 x 10⁻¹¹ kg</td>
<td>3.5 x 10⁻⁹ kg</td>
</tr>
<tr>
<td>Fluid Viscosity, μ</td>
<td>1.9 x 10⁻⁵ N-s/m²</td>
<td>1.9 x 10⁻⁵ N-s/m²</td>
<td>9 x 10⁻⁴ N-s/m²</td>
</tr>
<tr>
<td>Viscous Time Scale, τᵥ</td>
<td>9 ms</td>
<td>0.9 ms</td>
<td>0.19 ms</td>
</tr>
<tr>
<td>α = 0.1, So τ₅ is</td>
<td>0.9 ms</td>
<td>0.09 ms</td>
<td>0.019 ms</td>
</tr>
<tr>
<td>β = 1.5, So τ₅ is</td>
<td>14 ms</td>
<td>1.4 ms</td>
<td>0.42 ms</td>
</tr>
<tr>
<td>For β=1.5, ψᵣ is</td>
<td>0.6</td>
<td>0.6</td>
<td>0.6</td>
</tr>
<tr>
<td>Min. Wing Deflection, δᵣ</td>
<td>1.7 mm</td>
<td>17 µm</td>
<td>0.48 µm</td>
</tr>
<tr>
<td>Average Viscous Power, P</td>
<td></td>
<td>86 pW</td>
<td>0.48 nW</td>
</tr>
<tr>
<td>Peak Power, Pₘₐₓ</td>
<td></td>
<td>1.4 nW</td>
<td>11.5 nW</td>
</tr>
<tr>
<td>Reₘₐₓ=ρᵣδᵣl/(μτ₅)</td>
<td>0.99</td>
<td></td>
<td>28</td>
</tr>
</tbody>
</table>