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# REPORT DOCUMENTATION PAGE

**Title:** ENERGY-BASED DESIGN OF RECONFIGURABLE MICRO AERIAL VEHICLE (MAV) FLIGHT STRUCTURES

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**Abstract:**
The objective of the project is to understand how to mechanize multi-jointed MAV wings for perching and/or flapping applications and develop an energy-based design framework for the solution of combined multi-physics, multi-objective problems.

**Subject Terms:**
- micro air vehicle
- perching
- topology optimization

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Energy-Based Design of Reconfigurable MAV Flight Structures

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RQ Tech Division Consolidation

Aerospace Vehicles

High Speed Systems

Power and Control

Turbine Engine

Rocket Propulsion

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Motivation

- Biological systems not necessarily designed for optimal flight
- Engineered systems don’t have requirements related to feeding, care for young, etc.
- Should we be attempting to mimic natural systems, knowing that they are not optimized for flight?
- What would a biological system look like if optimized only for flight?
- Can we use engineering design and optimization to create a “flight-only estimate” of the biological system?
Objective

- Understand how to mechanize multi-jointed MAV wings for perching and/or flapping applications
- Develop an energy-based design framework for the solution of combined multi-physics, multi-objective problems
Technical Challenges

• Design tool for multi-physics analysis and optimization under unsteady aerodynamic load is not well established
• Identification of wing morphology requirements is not well understood
• Performance measures such as energy and efficiency measures for unsteady aerodynamic flight are not well defined
• Passive shape control to maximize energy efficiency is not well exploited
Approach

• Student 1 (AFIT) will focus on the distribution of skin material to meet performance objectives after selecting four snapshots of a bird wing configuration during perch

• Student 2 (UD) will extend the scope of the research to include active shape control (mechanism synthesis) in addition to skin material distribution
Wing Skin Structure Design

• Configuration Selection

Eagle Owl in Loiter, Dash, and Flare Configurations

Typical Perching Trajectory and Perching Wing Configurations
Wing Skin Structure Design

• Configuration Selection

Forward Swept Configuration

Zero Sweep Configuration

Back Swept Configuration

Dive Configuration

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Wing Skin Structure Design

- **Force Estimation**
  - Forces were calculated in MATLAB Vortex Lattice code called *Tornado*
  - *Zero-lift, flat-plate drag coefficient* estimated by Tornado
  - Drag coefficient related to angle of attack
  - Force on each panel split into four components and applied to the nodes

**Viscous Drag Estimation Curve**

**Example of Tornado Vortex Panels Output**

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Wing Skin Structure Design

- **Perching Data**

**Wing Configuration:**

*Point 1:* Back Swept

*Point 2:* Dive

*Point 3:* Zero Sweep

*Point 4:* Forward Swept
## Wing Skin Structure Design

### Force Estimation

- Induced drag is highest for Point 3, not Point 4, and lowest at Point 2
- Side forces have minimal influence on resulting topologies
- Lift highest for Point 3
- Axial body force pushes wing forward
- Most bending loads about 10 times the membrane loads
- Viscous drag is lowest at Point 4, even though the Point 4 is at a high angle of attack

### Aerodynamic Data for Birdwing Along Perching Trajectory

<table>
<thead>
<tr>
<th></th>
<th>Point 1</th>
<th>Point 2</th>
<th>Point 3</th>
<th>Point 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_{el}$ [m/s]</td>
<td></td>
<td>10</td>
<td>10.41</td>
<td>10.11</td>
</tr>
<tr>
<td>AOA [°]</td>
<td></td>
<td>6</td>
<td>3.75</td>
<td>10</td>
</tr>
<tr>
<td>$D_{drag}$ [N]</td>
<td>0.0176</td>
<td>0.0033</td>
<td>0.0796</td>
<td>0.0456</td>
</tr>
<tr>
<td>$S_{ide}$ [N]</td>
<td>0.0061</td>
<td>0.0075</td>
<td>-0.0007</td>
<td>-0.0087</td>
</tr>
<tr>
<td>$L_{ift}$ [N]</td>
<td>0.459</td>
<td>0.112</td>
<td>1.241</td>
<td>0.196</td>
</tr>
<tr>
<td>$F_{x}$ [N]</td>
<td>-0.0304</td>
<td>-0.0040</td>
<td>-0.1371</td>
<td>-0.1208</td>
</tr>
<tr>
<td>$F_{y}$ [N]</td>
<td>0.00610</td>
<td>0.00749</td>
<td>-0.0066</td>
<td>-0.00871</td>
</tr>
<tr>
<td>$F_{z}$ [N]</td>
<td>0.458</td>
<td>0.112</td>
<td>1.236</td>
<td>0.161</td>
</tr>
<tr>
<td>$C_{L}$</td>
<td>-0.220</td>
<td>0.076</td>
<td>0.512</td>
<td>1.701</td>
</tr>
<tr>
<td>$C_{D}$</td>
<td>-0.0085</td>
<td>0.0022</td>
<td>0.0328</td>
<td>0.3958</td>
</tr>
<tr>
<td>$C_{Y}$</td>
<td>-0.0029</td>
<td>0.0051</td>
<td>-0.0003</td>
<td>-0.0757</td>
</tr>
<tr>
<td>$R_{e}$</td>
<td>-90054</td>
<td>137712</td>
<td>91412</td>
<td>19987</td>
</tr>
<tr>
<td>$C_{D_{0}}$</td>
<td>-0.0101</td>
<td>0.0082</td>
<td>0.0101</td>
<td>0.0113</td>
</tr>
<tr>
<td>$S_{weft}$ [m²]</td>
<td>0.0681</td>
<td>0.0444</td>
<td>0.0775</td>
<td>0.0785</td>
</tr>
<tr>
<td>$D_{vis}$ [N]</td>
<td>0.2368</td>
<td>0.1077</td>
<td>0.4410</td>
<td>0.0885</td>
</tr>
<tr>
<td>Normal [N]</td>
<td>0.248</td>
<td>0.0070</td>
<td>0.0766</td>
<td>0.0678</td>
</tr>
<tr>
<td>Axial [N]</td>
<td>0.2355</td>
<td>0.1075</td>
<td>0.4343</td>
<td>0.0569</td>
</tr>
</tbody>
</table>

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Wing Skin Structure Design

• Results – Point 1

Membrane

Bending

Combined

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Wing Skin Structure Design

• Results – Point 2

Membrane

Bending

Combined

(c) \( V_{ol_f} = 0.1 \)

(b) \( V_{ol_f} = 0.5 \)

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Wing Skin Structure Design

• Results – Point 3

Membrane

(a) $V_{ol_f} = 0.2$
(b) $V_{ol_f} = 0.3$
(c) $V_{ol_f} = 0.4$

Bending

(a) $V_{ol_f} = 0.2$
(b) $V_{ol_f} = 0.3$
(c) $V_{ol_f} = 0.4$
(d) $V_{ol_f} = 0.5$

Combined

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Wing Skin Structure Design

• Results – Point 4

Membrane

(a) Vol_f = 0.2
(b) Vol_f = 0.3
(c) Vol_f = 0.4
(d) Vol_f

Bending

(a) Vol_f = 0.2
(b) Vol_f = 0.3
(c) Vol_f = 0.4
(d) Vol_f = 0.5

Combined

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Wing Skin Structure Design

• Summary
  – In general, structural members support the leading edge
  – Membrane solutions resemble truss-like structures, and bending solutions resemble beam-like structures
  – Membrane solutions clearly dominate the combined loading
  – When the viscous drag distributed over the surface of the wing is not considered, hybrid solutions occur
  – Secondary features include straight battens in membrane structures, and branches in bending structures
  – Membrane solution must support out-of-plane loading, so discrete “truss” members must function like spars
  – The topology constantly changes at different points along perching trajectory so we need an active mechanism to reconfigure at different loading conditions → Wing mechanism design

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Previous Research
(Multiple Configurations)

- Generic Surveillance UAV with three configurations
  - Loiter (configuration 0 = reference)
  - High lift (configuration 1)
  - Climb (configuration 2)
Wing Mechanism Design

• Developing design tool for energy-based optimization of structure topology

• Currently includes…
  – Geometry Generator
  – Pre-Processor
  – Structural Analysis
  – Optimization Routine
  – Aerodynamic Analysis (in progress)
  – Post-Processor (in progress)
Wing Mechanism Design

• **Geometry Generator/Preprocessor**
  - Includes a GUI for ease of use
  - Creates a parametrically defined wing geometry

• Facilitates future optimization routines that could update body geometry

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Wing Mechanism Design

- Box Substructure Description

16 Nodes

4 Nodes
Wing Mechanism Design

• Structural Analysis
  – Implements Standard finite element approach
  – Uses a condensed frame element with rotational springs on each end
  – Reduces DoFs thereby decreasing computational time and simplifies programming
Wing Mechanism Design

• Optimization Routine
  – Globally Convergent Method of Moving Asymptotes
    • Developed by Svanberg
    • One of the most used methods for structural optimization
  – Problem Formulation
    • Minimize:
      – Shape Error and Actuator Usage
    • Subject to:
      – Static Equilibrium
      – Stroke Limit
      – Attachment Stiffness
      – +/- Volume Fraction

Minimize:

\[ f_0 = W_1 \sum_{i \in T} (U_{i}^{\text{target}} - U_{i})^2 + W_2 \sum_{i \in A} \rho_j^2 \]

Subject to:

\[ f_{\text{eq}} = KU - F = 0 \]
\[ f_m = E_m^2 - E_{\text{max}}^2 \leq 0 \]
\[ f_F = \sum_{i \in B} \rho_i - N_F \leq 0 \]
\[ f_{+V} = \sum_{i \in L_1} \rho_i + \sum_{i \in L_2} \rho - V_{\text{max}} \leq 0 \]
\[ f_{-V} = - \sum_{i \in L_1} \rho_i - \sum_{i \in L_2} \rho + V_{\text{min}} \leq 0 \]
Wing Mechanism Design

• Aerodynamic Analysis (in progress)
  – Extracting Aerodynamic Influence Coefficient (AIC) matrix from Tornado for use in a static aeroelastic analysis
  – Coupling aerodynamic loads and structural deformation
  – Leveraging the aeroelastic deformation, it is assumed a reduced use in energy design may be found

• Post-Processor
  – Clearly displays the results from the design tool
Research Plans for Next FY

- Key energy metrics and efficiency measures for optimal multi-physics designs
- Design methodology to determine passive and active shape control for efficient vehicle flight performance
- Comparison of engineering and evolutionary optimal solutions for similar systems
Backup
Approach

• Utilize design optimization techniques for efficient design of aeroelastic reconfigurable systems incorporating distributed actuation and compliance

• Develop flight energy and efficiency measures for topology optimization

• Provide understanding of a systematic design process for a bio-mimetic vehicle design problem

• Select “snapshots” of vehicle in perching maneuver at different times

• Optimize based on multiple load conditions

• Identify suitable objective functions to produce “good” designs
Approach

- Student 2 (UD) will extend the scope of the research to include mechanism design scheme in addition to skin material distribution
Wing Skin Structure Design

• **Optimality Criteria Method**
  
  – OC method is a bisection method based on the fact that the material volume is a monotonically decreasing function of the Lagrange multiplier
  
  – Stationarity point is achieved when volume constraint is satisfied
  
  – Update scheme given by:
    
    $\rho_{e}^{k+1} = \min \left\{ \max \left[ \rho_{e}^{k} \left( \frac{q_{e}(g_{e})^{-1}(d_{e}^{k})^{T}k_{e}^{T}d_{e}^{k})^{\eta}}{\lambda a_{e}} \right), \rho_{\min} \right], \rho_{\max} \right\}$

    such that the volume constraint satisfies

    $\sum_{e=1}^{N} a_{e}\rho_{e}^{k+1}(\lambda) - V = 0$

  
  – OC method closely related to fully stressed design, where all elements have same strain energy; not exactly the case, because of SIMP model
Previous Research
(Flexible Skin Design)

- Two-step topology optimization process
  - Step 1: distribution of bulk material properties
  - Step 2: distribution of multi-phase material

Example Target Shapes

Notional Substructure

Two Phase Material Solution

\[
p_E \Rightarrow E_{ijkl}^e (p_E) = p_E^{\beta} E_{ijkl}^1 + \left(1 - p_E^{\beta}\right) E_{ijkl}^2
\]

Target Reduced Stiffness Matrix

\[
Q^* = \begin{bmatrix}
1.6979 & 0.6230 & 0 \\
0.6230 & 1.8880 & 0 \\
0 & 0 & 0.5066
\end{bmatrix} \times 10^3
\]

Reduced Stiffness Matrix from Homogenization Routine

\[
Q'' = \begin{bmatrix}
1.7179 & 0.6076 & 0 \\
0.6076 & 1.9021 & 0 \\
0 & 0 & 0.5184
\end{bmatrix} \times 10^3
\]

Turning Theory Into Application
Reducing Design Time

Ad Hoc Solution

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Wing Skin Structure Design

• Finite Element Derivation
  – Membrane Element
  – Bending Element
  – Combined Membrane/Bending Element

*Superimposed membrane and bending plate models to form 6-dof model*

\[
\begin{bmatrix}
\{ f_m \} \\
\{ f_b \} \\
\{ f_{\theta z} \}
\end{bmatrix}
= 
\begin{bmatrix}
[k_m] & [0] & [0] \\
[0] & [k_b] & [0] \\
[0] & [0] & [k_{\theta z}]
\end{bmatrix}
\begin{bmatrix}
\{ d_m \} \\
\{ d_b \} \\
\{ d_{\theta z} \}
\end{bmatrix}
\]

*Fictitious stiffness matrix added for “drilling” degrees of freedom to avoid singularities*

\[
\begin{bmatrix}
M_{z1} \\
M_{z2} \\
M_{z3} \\
M_{z4}
\end{bmatrix}
= \alpha EV
\begin{bmatrix}
1.0 & -0.5 & -0.5 & -0.5 \\
-0.5 & 1.0 & -0.5 & -0.5 \\
-0.5 & -0.5 & 1.0 & -0.5 \\
-0.5 & -0.5 & -0.5 & 1.0
\end{bmatrix}
\begin{bmatrix}
\theta_{z1} \\
\theta_{z2} \\
\theta_{z3} \\
\theta_{z4}
\end{bmatrix}
\]
• **Topology Optimization**
  
  – Minimizing compliance equivalent to maximizing stiffness
  
  – Compliance is equivalent to the strain energy of a deformed structure
  
  – Volume constraint is added to avoid infinite stiffness
  
  – Nested compliance minimization optimization statement:

\[
\min_{\rho} \ c(\rho) \\
\text{s.t. } \{\rho\}^T\{a\} - V = 0, \quad 0 < \rho_{\text{min}} \leq \rho_e \leq \rho_{\text{max}}, \quad e = 1, \ldots, N
\]

where the compliance \( c \) is defined by

\[
c(\rho) = \{F\}^T\{d\}, \quad \text{where } \{d\} \text{ solves: } \left( \sum_{e=1}^{N} [k_e] \right) \{d\} = \{F\}
\]
Wing Mechanism Design

- **Geometry Generator/Preprocessor**
  - Generates varying degrees of mesh connectivity for the initial ground structure topology

![Degree of Connectivity = 1](image1)

![Degree of Connectivity = 2](image2)
Wing Skin Structure Design

- **Solid Isotropic Material with Penalization (SIMP)**
  - Penalizes intermediate thickness values, driving thicknesses towards a discrete solution
  - Thicknesses are penalized by raising the element thickness to a power greater than 1 in the constitutive matrix:

\[
[D] = \frac{\rho^q E t}{1 - \nu^2} \begin{bmatrix} 1 & \nu & 0 \\ \nu & 1 & 0 \\ 0 & 0 & \frac{1 - \nu}{2} \end{bmatrix}
\]

**SIMP Penalization of Element Thickness**

(a) After 5 Iterations  (b) After 10 Iterations  (c) After 15 Iterations
(d) After 20 Iterations  (e) After 50 Iterations  (f) After 298 Iterations