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• Introduction to aeroelasticity
  – Static and dynamic aeroelasticity
• Traditional Aircraft Structural Design
• Morphing Structures
  – Configuration morphing
  – Performance morphing
    • Adaptive Internal Structures
    • Adaptive Stiffness Attachments
• Optimisation requirements
• Optimisation approach
• Some results and conclusions
• Interaction of aerodynamic forces with elastic bodies

• Many applications: aircraft, cars, bridges, chimneys, turbine blades
103 Years Ago

- Wright brothers were perfecting their “Flyer” at Kitty Hawk.

- Samuel Langley, backed by the Smithsonian Institute, attempted to fly his “Aerodrome” off a houseboat on the Potomac River.
Langley’s Tests

- Structural failure
First Known Aeroelastic Failure

- Wings were not stiff enough
- “Divergence” – torsional loads overcome structural restoring forces
- “Aerodrome” rebuilt some years later by Curtis with stiffer wings – it flew
- Interaction of flexible structure and aerodynamic forces need to be considered
- Science of Aeroelasticity
Wright Brothers

- Success
- Wing warping for roll control
Aeroelastic Phenomena

- Mostly undesirable
- Often catastrophic
- Static and dynamic effects
- Linear and non-linear response
- Key criteria
  - certification
  - aircraft performance
- Still unable to accurately predict some types of behaviour
Flutter

- Most important of aeroelastic phenomena
- Dynamic phenomenon
- Violent unstable vibration often resulting in structural failure
- Two modes interact with each other and extract energy from the airflow
Test of “Wing” at NASA Dryden
Aeroelastic Design

- Most aeroelastic phenomena are undesirable
- Traditional design has built stiff heavy structures to eliminate aeroelastic effects
- Recent change in design approach - use aeroelasticity in a positive manner
  - Lighter, adaptive, more efficient structures
  - Better aeroelastic effectiveness
  - Static control of twist and bending
  - Optimal drag configuration
  - Roll control
  - Loads Control
Not a New Idea

All-movable “drag control” devices
Active camber control
Active leading edge surfaces

(Lilienthal “Vorflügelapparat” 1895)
Two Classes of Morphing (1)

- Configuration Morphing
  - Change in planform
    - Aircraft control
    - Aircraft performance
  - Change in mission
    - High aspect-ratio glide
    - Attack mode
Previous Configuration Morphing Structures

Change aircraft shape during flight
Two Classes of Morphing (2)

- Performance Morphing
  - Change in structural properties
    - Stiffness
    - Camber
    - Leading / trailing edge shape
  - Aircraft control
  - Aircraft performance
    - Lift / drag
    - Roll control
    - Loads
- Adaptive Aeroelastic Structures
Adaptive Stiffness Vertical Tails

- Conventional design
  - Large, high aspect ratio structure
  - Multiple attachments
  - Large loads
  - Susceptible to buffet
  - Stiff, heavy structures
  - Drag & radar cross-section penalties

- MDO methods have been applied to reduce weight using composites
All-Moving Vertical Tail

• Replace large multiple attachment VT with smaller and lighter single attachment VT
Effect of Single Attachment Position and Torsional Stiffness on Benchmark Fin

- Aft attachment and reduced torsional stiffness gives greater efficiency
Aeroelastic Stability Must be Maintained

Flutter Speed

Attachment Torsional Stiffness (Nmm/rad)

Attachment moving aft
Conflict Between Efficiency Gains and Aeroelastic Stability

- Aft attachment and reduced torsional stiffness gives greater efficiency
- But.....
  - reduced torsional stiffness reduces the flutter and divergence speeds
  - Need high torsional stiffness for landing case
- Need adaptive torsional stiffness to change torsional stiffness depending upon flight condition
Pneumatic Adaptive Stiffness Device
Calibration of Stiffness Device

Max pressure depends upon the cylinder size
Wind Tunnel Testing of VT Component with Pneumatic Stiffness Device
Measured Fin Efficiencies

FIN EFFICIENCY vs TORSIONAL STIFNESS

50% MAC

Fin Efficiency

Torsional Stiffness Nm/rad

5 m/s
10 m/s
15 m/s
20 m/s

50% MAC
Freeplay Tests

TIME DOMAIN WAVEFORM (ROTATION FROM +10 TO -10 DEGREES)

ANGLE (degrees)

TIME (sec)

-6
-4
-2
0
2
4
6
8
10
12
14
16
18
20

-6
-4
-2
0
2
4
6
8
10
12
14
16
18
20

4 BAR 50%MAC 10 m/s
Tests on EuRAM Model
Sensorcraft Requirements

- Unmanned
- High Altitude
- Long endurance
- Low / moderate stealth
- All round coverage
- Modular payloads
- Reasonable speed
• Much recent interest
• 360° sensing
• High AR wing
• Structural stiffening from second wing
Structural Design

- Critical buckling cases
  - increased structure required
- If gust loads could be relieved
  - reduced structure required

(a) Linear
(b) Non-Linear Analysis
Gust Alleviation

- Active systems
  - control surfaces
  - require active control technology

- Passive systems
  - don’t need sensors / computer etc.
  - less to go wrong
  - not optimal for every gust case
Gust Alleviation Device

- Passive Device
- Vertical Gust causes nose down twist
- Adaptive stiffness
  - adaptive aeroelastic technology
  - use as trim and roll manoeuvre

Inboard wing section

Torque tube

Out board section
Baseline Model

Only Symmetric Modes considered

“Cut” and attachment
Initial Gust Results

Gust Alleviation device gives worse results than baseline
Magnified Stress Contour
Optimisation Process

- Biological growth inspired approach
- Consider range of flight conditions, load cases, torsional device stiffness
- Linear aerodynamics (M=0.6)
- Add structure to areas of high stress
- Remove structure from areas of low stress
- Constraints
  - stress
  - flutter / divergence
    - add mass a wing tip leading edge
  - linear buckling
    - add mass at points of greatest curvature in buckling shape
After Optimisation
Optimisation Iterations

Element Thickness for Front Section

- Base-Top
- Base-Bottom
- Base-Rib
- Base-Spar
- Mid-Top
- Mid-Bottom
- Mid-Rib
- Mid-Spar
- Tip-Top
- Tip-Bottom
- Tip-Rib
- Tip-Spar

Thickness (m)

Iteration

$5 \times 10^{-3}$
Mass Changes

Mass changes for Sensorcraft

<table>
<thead>
<tr>
<th>Iteration</th>
<th>Mass (kg)</th>
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<tbody>
<tr>
<td>0</td>
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</table>
Adaptive Internal Structures

- Exploit changes in internal structure
  - alter position of flexural axis
  - change 2nd moment of area / torsion constant
- Change wing deflection and twist
- All energy for twist provided by the aerodynamic lift
- Applications
  - Drag reduction
  - Roll control
- Number of concepts under consideration
  - FE / Aeroelastic analysis / bench wind tunnel tests
Moving Spars Concept

- Move spars chordwise
- Changes the torsional stiffness and shear centre position
- Bending stiffness remains the same
- Simple drive motors used to move spars via worm drive or pneumatic pistons

High torsional stiffness

Low torsional stiffness
Analytical Demonstration of Concept

Fixed Spars

Moveable Spar

Skins
Effect of Changing Middle Spar Position

- Shear
- Twist
- Vflutter
- Vdiv

% chord position of middle spar
Wind Tunnel Test Deflections
Rotating Spars Concept

- Change orientation of spars.
- Beams in horizontal position
  - stiffness minimum
- Beams in vertical position
  - stiffness maximum
- Use pairs of spars to control bending and torsion
- Influence on
  - Shear centre position
  - Torsion constant
  - Bending stiffness

High stiffness

Low stiffness
ERCOFTAC 2006: Towards the Optimisation of Adaptive Aeroelastic Structures

Analytical Demonstration of Concept

Rotating Spars

Skins
Variation of $I_{xx}$
Variation of Shear Centre Position

position of shear centre (fraction of chord)

\( \theta_1 \) (deg)  \( \theta_2 \) (deg)
Rotation of Spars
Prediction of $C_L$, $C_D$, $C_L/C_D$
Wind Tunnel Test Results
Control-Surface Free Version of RQ-7 Shadow 200 Tactical UAV

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<thead>
<tr>
<th>Specification</th>
<th>Value</th>
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<tbody>
<tr>
<td>Weight</td>
<td>149 kg</td>
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<tr>
<td>Payload</td>
<td>27 kg</td>
</tr>
<tr>
<td>Length</td>
<td>3.36 m</td>
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<tr>
<td>Wingspan</td>
<td>3.84 m</td>
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<tr>
<td>Ceiling</td>
<td>4.5 km</td>
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<tr>
<td>Radius</td>
<td>68 nm</td>
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<tr>
<td>Endurance</td>
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Ref: http://www.globalsecurity.org/intell/systems/shadow.htm
Tip Twist Angle for Front and Rear Spar Rotation

Change of Tip Angle for Different Angles of Front and Rear Spar Rotation

Angle of Tip Twist (deg)

theta 2 (deg)  
20 40 60 80 100

0 2 4

theta 1 (deg)  
0 20 40 60 80 100
Rolling Rate for Front and Rear Spar Rotation

Change of Rolling Rate for Different Angles of Front and Rear Spar Rotation relative to the angle at 15 and 75 deg, respectively.
Optimisation Requirements

• What stiffness distribution will give minimum drag at different altitudes, speeds and fuel conditions whilst meeting constraints?
Genetic Algorithms

- Directed random search algorithm
- Based upon Darwinian theory of natural selection
- Binary representation of genes
- Changing random parameters
  - vary through iterative process
- Penalty Functions
  - vary through the iterative process
Particle Swarm Optimisation

- Mimics a swarm that flies over the search space
- Each particle knows what was the best point
  - for itself
  - for the swarm
- Next direction and velocity dependent upon this information

\[
\begin{align*}
  v_{\text{new}} &= v_{\text{old}} + c_1r(p_b - pos) + c_2r(s_b - pos) \\
  \text{pos} &= \text{pos}_{\text{old}} + v_{\text{new}}
\end{align*}
\]

- Memory and competition
Example of PSO(1)
Example of PSO(2)
Parameters

- Vary the stiffness of each spar
- Determine
  - Lift
  - Drag
  - Flutter
  - Divergence
Variation of Lift for 8 Spars

Coefficient of Lift vs Configurations

Reference Lift
Optimisation

• Aircraft parameters
  – fuel cases
  – altitude and speed

• Optimisation parameters
  – Stiffness of the spars and ribs

• Objective
  – Determine the minimum amount of change in the structure to minimise the drag

• Constraints
  – Flutter / divergence
Initial Results

- Objectives achieved through use of outer spars and ribs
Future Work

• Minimum mass design
• Shape optimisation
  – Position of ribs and spars
• Use of higher fidelity drag models
• Inclusion of roll-rate / loads alleviation
• Improved adaptive stiffness devices
• Use of smart materials / devices
Thank you for your attention

Any questions?