Optimization Framework for Design of Morphing Wings

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Traditional Aircraft Design

- Single point for the design
  - Minimum weight
  - Maximum $C_L/C_D$
  - Suboptimal elsewhere

maximise cruise speed – ie cruise at high altitude

$$R = \frac{V}{fg} \left( \frac{C_L}{C_D} \ln \left( \frac{W_1}{W_2} \right) \right)$$

a measure of thermodynamic efficiency – ie minimise fuel consumption $f$

a measure of aerodynamic efficiency – ie minimise drag $D$

a measure of structural efficiency – ie minimise fixed weight $W_2$
Morphing, when applied to aerospace vehicles, is a technology or set of technologies applied to a vehicle that allow its characteristics to be changed to achieve better performance or to allow the vehicle to complete tasks it could not otherwise do.

Jason Bowman, AFRL/VSSV
Configuration Morphing

• Change in planform
  – Aircraft control
  – Aircraft performance

• Change in mission
  – High aspect-ratio glide
  – Attack mode

MFX 1, Span & Sweep
Configuration Morphing

(Joshi et al., 2004, AIAA)
Performance Morphing

• Change in structural properties
  – Stiffness
  – Camber
  – Leading / trailing edge shape

• Aircraft control

• Aircraft performance
  – Lift / drag
  – Roll control
  – Loads
Variable Stiffness Morphing

- Range of different adaptive stiffness methodologies to be explored
- Vary $EI_x$, $EI_y$, GJ, flexural axis using changes in internal structure
- Changes to spar orientation, rib position, spar cap position – used in several previous EU projects
  - 3AS, SMorph, NOVEMOR
Aims

• Develop an inverse design approach
  - optimise internal wing stiffness distribution
  - morphing capability.

• Meet optimal aerodynamic shape throughout the flight envelope

• Define the required changes in stiffness / elastic axis

• Minimize the amount of morphing

• Minimize the weight

• Satisfy any other constraints – to be defined progressively
Inverse Design Approach

- Define required aerodynamic distributions
- Define required wing shapes – Twist / camber / bending
- Optimise weight to determine stiffness distributions
- Evaluate required stiffness changes
- Determine morphing concept(s) to achieve stiffness changes

![Diagram showing the inverse design approach process]

**Flight Condition 1**
- Aerodynamic pressure distribution
  - Aeroelastic shape

**Flight Condition 2**
- Aerodynamic pressure distribution
  - Aeroelastic shape

**Structural Optimisation**
- Static Aeroelastic Weight Optimisation
  - Stiffness Distribution and Jig Shape

**Morphing requirements**
Wing Aerodynamic shape
Via Lifting Surface VL or DL (lattice) (Lamar) mean camber for minimum drag

• Planform dimensions

<table>
<thead>
<tr>
<th></th>
<th>wing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aspect ratio (AR)</td>
<td>12</td>
</tr>
<tr>
<td>Taper ratio</td>
<td>0.5</td>
</tr>
<tr>
<td>Sweep angle</td>
<td>10 degrees</td>
</tr>
<tr>
<td>Semi-span</td>
<td>20 meters</td>
</tr>
</tbody>
</table>

Camber lines required to achieve M0.74 loading

Vortex panels

Mean camber lines
Aerodynamic shape design
- Lifting Surface, Mach Effect

- $\Delta C_p$ distributions

Design for 4 different test cases – thin lifting surface
Aerodynamic shape

- Super-Critical (twist & Camber)
- Panel & Euler (AR=12, Ma=0.74)
Aerodynamic shape
Different approaches, 0.5 $C_L$
Structural model

(a) 

(b) 

Cross section

- wingbox, front
- wingbox, rear
- centre line

$t_L$, $t_R$, $t_H$,
$l$, $b_c$, $d$
Weight Optimisation

Minimize weight

\[ W(t) = \rho \sum_{i=1}^{N_e} [2b_c t_{Hi} + d(t_{Li} + t_{Ri})] l \]

subject to

\[ g_j(u, t) \geq 0, \ j = 1, \ldots, n_j. \quad \text{(constraint functions)} \]

• Consider deflection/stress constraints & minimum gauge of design variables.

• Use optimality criteria method
Application: Aero design

Mach 0.74

Camber, M0.74

ΔCp, M0.74

Cp√x, M0.74

Mach 0.6

Camber, M0.6

ΔCp, M0.6

Cp√x, M0.6

Mach 0.4

Camber, M0.4

ΔCp, M0.4

Cp√x, M0.4

Mach 0.25

Camber, M0.25

ΔCp, M0.25

Cp√x, M0.25
$\Delta C_p$ (using M0.74 camber)

(a) $\Delta C_p$, M0.6

(b) $\Delta C_p$, M0.4

(c) $\Delta C_p$, M0.25

(d) $\Delta C_{p\sqrt{x}}$, M0.6

(e) $\Delta C_{p\sqrt{x}}$, M0.4

(f) $\Delta C_{p\sqrt{x}}$, M0.25
Spanwise loadings - effect of M

Non-D by CL

0.74M camber. Evaluated at different test cases
Local AoA required to achieve reference loading of **M0.74** with M0.74 camber.
$\Delta C_p$ Distributions before --- & after adding twist ---

$\Delta C_p$ & $\Delta C_p \sqrt{x}$

30% Note
Structural Optimisation, 0.74M solution process

Weight Convergence - fast

Flex. axis varies as function of $t_R / t_L$
Predicted Jig shapes & Twist, different M

Using M0.74 camber
Achieving M0.74 pressure dist using wingbox twist only
Morphing required
(Twist only example from half span)

Elastic twist

GJ

ΔGJ
Morphing required
(Twist & camber morphing example)
Morphing required
(Twist & camber morphing example)

Elastic twist

GJ

ΔGJ

Note Strong Reduction
Twist & camber
Camber morphing case

- TE Morph: to achieve desired spanwise loading and reduce RBM
LE morphing effects

- LE Morph: to reduce leading edge suction and flow separation

(a) M0.25, Without LE morphing

(b) M0.25, With LE morphing
LE morphing

(a) M0.25, constant LE morphing
(b) M0.25, varying LE morphing

(c) 

\[ \Delta C_P \]

\[ x/c \quad 1 \quad 0 \quad y/s \]

\[ 0 \quad 0.5 \quad 1 \]

\[ -1 \quad 0 \quad 1 \]

\[ 0 \quad 1 \quad 2 \quad 3 \]

\[ \Delta C_P \]

\[ x/c \quad 1 \quad 0 \quad y/s \]

\[ 0 \quad 0.5 \quad 1 \]

\[ -1 \quad 0 \quad 1 \]

\[ 0 \quad 1 \quad 2 \quad 3 \]

(c) 

\[ \text{LE droop angle (degs)} \]

\[ 0 \quad 5 \quad 10 \quad 15 \quad 20 \]

\[ y/s \]

- constant LE morph
- varying LE morph
Mean camber shape

- Variations from M 0.74 to M 0.25 case
Conclusions

• Multiple point design useful for enhancing aircraft efficiency
• Adaptive wing / morphing concepts reviewed
• An inverse design approach to optimise the internal stiffness distribution & morphing capabilities
• Application to a regional aircraft wing
• Weight reductions achieved via structural optimisation
• Required morphing examined to meet the multi-design points
• Need a lot of twist morphing to achieve required shape over flight envelope
• Use of camber morphing reduces the amount of required twist
Ongoing Work

• Continue with aerodynamic shape determination
  – Configuration / flight conditions (Panel, Euler)
  – Winglet
  – Controls

• Implement inverse approach on coupled-beam model, using more advanced Aero
  – Panel & Euler, Bodies

• Determine required stiffness variations in terms of morphing approaches

• Investigate reasonable morphing requirements
PANAIR Results

- M0.25, varying twist
Euler results

Design M 0.74

Off-design, Mach 0.6