Dynamic Aeroelastic Scaling of the CRM Wing via Multidisciplinary Optimization

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WCSMO12

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Reference aircraft
Introduction - Similarity and Optimization

Reference aircraft

Scaled model

Thickesses → Passive action on [K] & [M]
Moving Masses →
Active action on [M]

PZT → Active action on [K]

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Introduction - Similarity and Optimization

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Active action on $[M]$

PZT $\rightarrow$ Active action on $[K]$

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Introduction - Dynamic Aeroelastic Similarity

Reference aircraft mode shape

Optimized scale demonstrator mode shape

* [Richards et al., AIAA/ATIO Conference, 2010]
Outline

1. Tools
2. Dynamic Aeroelastic Scaling
3. CRM wing modal optimization
4. Aerodynamic Flutter Optimization
5. Conclusion
6. Perspectives
1 Tools

2 Dynamic Aeroelastic Scaling

3 CRM wing modal optimization

4 Aerodynamic Flutter Optimization

5 Conclusion

6 Perspectives
- Nastran 95*: Normal Modes and Flutter Analysis
Tools

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- Panair/a502†: Static aerodynamics
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- OpenMDAO‡ Framework
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- Optimizer: SLSQP (Gradient-based, from Scipy library)
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* [github.com/nasa/NASTRAN-95]
† [pdas.com/panair.html]
‡ [Gray et al., AIAA/ISSMO, 2014]
1 Tools

2 Dynamic Aeroelastic Scaling

3 CRM wing modal optimization

4 Aerodynamic Flutter Optimization

5 Conclusion

6 Perspectives
Dynamic Aeroelastic Scaling

Aeroelastic equations of motion:

\[
[M]{\ddot{x}} + [K]{x} = [A_k]{x} + [A_c]{\dot{x}} + [A_m]{\ddot{x}} + [M]{a_g}
\]

[Ricciardi et al., Journal of Aircraft, 2014]
Dynamic Aeroelastic Scaling

Aeroelastic equations of motion:

$$[M]\{\ddot{x}\} + [K]\{x\} = [A_k]\{x\} + [A_c]\{\dot{x}\} + [A_m]\{\ddot{x}\} + [M]\{a_g\}$$

In modal coordinates ($\{x\} = [\Phi]\{\eta\}$):
Dynamic Aeroelastic Scaling

Aeroelastic equations of motion:

\[ [M] \{\ddot{x}\} + [K]\{x\} = [A_k]\{x\} + [A_c]\{\dot{x}\} + [A_m]\{\ddot{x}\} + [M]\{a_g\} \]

In modal coordinates (\{x\} = [\Phi]\{\eta\}):

\[
\]
Dynamic Aeroelastic Scaling

Aeroelastic equations of motion:

\[
[M]\dddot{x} + [K]x = [A_k]x + [A_c]\dot{x} + [A_m]\ddot{x} + [M]a_g
\]

In modal coordinates (\(\{x\} = [\Phi]\{\eta\}\)):

\[
[\Phi]^T[M][\Phi]\dddot{\eta} + [\Phi]^T[K][\Phi]\{\eta\} = [\Phi]^T[A_k][\Phi]\{\eta\} +

[\Phi]^T[A_c][\Phi]\dot{\eta} + [\Phi]^T[A_m][\Phi]\ddot{\eta} + \frac{1}{b}[\Phi]^T[M]a_g
\]

[Ricciardi et al., Journal of Aircraft, 2014]
Dynamic Aeroelastic Scaling

Adimensionalize with reference quantities:

\[
\langle \tilde{m} \rangle \{^* \eta \} + \langle \tilde{m} \tilde{\omega}^2 \rangle \{ \eta \} = \frac{V^2}{b^2 \omega_1^2} \frac{gb}{V^2} \langle \tilde{m} \rangle [\Phi]^{-1} \{ \tilde{a}_g \} \\
+ \frac{1}{2} \frac{\rho S b}{m_1} \frac{V^2}{\omega_1^2 b^2} \left( \left[ \tilde{a}_k \right] \{ \eta \} + \frac{\omega_1 b}{V} \left[ \tilde{a}_c \right] \{ \eta \} + \frac{\omega_1^2 b^2}{V^2} \left[ \tilde{a}_m \right] \{ \eta \} \right)
\]
Traditional Dynamic Aeroelastic Scaling

Nondimensional aeroelastic equations of motion (harmonic solution):

Reference aircraft: \( r \)

Scaled model: \( m \)

\[
\langle \ddot{\mathbf{m}}_r \rangle \{\eta\} + \langle \dot{\mathbf{m}}_r \ddot{\omega}_r \{\eta\} = \frac{1}{2} \frac{\mu_{1r}}{\kappa_{1r}^2} [\mathbf{a}_{hr}(X_{ar}, \kappa, M_r)]\{\eta\}
\]

\[
\langle \ddot{\mathbf{m}}_m \rangle \{\eta\} + \langle \dot{\mathbf{m}}_m \ddot{\omega}_m \{\eta\} = \frac{1}{2} \frac{\mu_{1m}}{\kappa_{1m}^2} [\mathbf{a}_{hm}(X_{am}, \kappa, M_m)]\{\eta\}
\]
Traditional Dynamic Aeroelastic Scaling

Nondimensional aeroelastic equations of motion (harmonic solution):
Reference aircraft: \( r \)
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\langle \bar{m}_r \rangle \{ \dddot{\eta} \} + \langle \bar{m}_r \bar{\omega}_r^2 \rangle \{ \eta \} = \frac{1}{2} \frac{\mu_{1r}}{\kappa_{1r}^2} \left[ \bar{a}_{hr}(X_{ar}, \kappa, M_r) \right] \{ \eta \}
\]

Match \([\Phi], \langle \bar{\omega} \rangle, \langle \bar{m} \rangle\)
(from the problem \( K - \omega^2 [M] \{ \phi \} = 0 \))
through optimization

\[
\langle \bar{m}_m \rangle \{ \dddot{\eta} \} + \langle \bar{m}_m \bar{\omega}_m^2 \rangle \{ \eta \} = \frac{1}{2} \frac{\mu_{1m}}{\kappa_{1m}^2} \left[ \bar{a}_{hm}(X_{am}, \kappa, M_m) \right] \{ \eta \}
\]

Equal if same aerodynamic shape and flow similarity
1 Tools

2 Dynamic Aeroelastic Scaling

3 CRM wing modal optimization

4 Aerodynamic Flutter Optimization

5 Conclusion

6 Perspectives
CRM Model

Reference Design* (jig shape): For all elements $t_r = 8.89\,mm$

Model provided by T. Achard and C. Blondeau*

* [Achard et al., AIAA/ISSMO, 2016]
CRM modal optimization: Problem definition

Hypothesis: Flow similarity assumed

Objective Function

<table>
<thead>
<tr>
<th>Objective Function</th>
<th>Dimension</th>
<th>Bounds</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mode shape difference minimization ( \min(N - \text{trace}(\text{MAC}([\Phi_r], [\Phi_m]))) )</td>
<td>( \mathbb{R} )</td>
<td>[0.0889, 26.67] mm</td>
</tr>
</tbody>
</table>

Design Variables

<table>
<thead>
<tr>
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<th>Bounds</th>
</tr>
</thead>
<tbody>
<tr>
<td>Skin thicknesses vector ( [t] )</td>
<td>( \mathbb{R}^{10} )</td>
<td>[0.0889, 26.67] mm</td>
</tr>
</tbody>
</table>

Constraints

<table>
<thead>
<tr>
<th>Constraints</th>
<th>Dimension</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Reduced frequency matching ( |\omega_r - \omega_m| = 0 )</td>
<td>( \mathbb{R} )</td>
<td></td>
</tr>
<tr>
<td>Mass matching ( M_r - M_m = 0 )</td>
<td>( \mathbb{R} )</td>
<td></td>
</tr>
<tr>
<td>Generalized masses matching ( m_r - m_m = 0 )</td>
<td>( \mathbb{R} )</td>
<td></td>
</tr>
</tbody>
</table>

→ Upper skin panels

Lower skin panels ←
Traditional Modal Optimization

Hypothesis: Flow similarity assumed

\[ t_0, 3 \rightarrow 1: \text{Optimization} \]

1: Nastran Modal Analysis

2: Objective Function

3: Frequency

1: \( \Phi \) \( \omega \) \( M \)

2: \( \Phi \) \( \omega \) \( M \)

3: \( f \) \( c_1 \) \( c_2 \) \( c_3 \)

2: Mass

2: Generalized Modal Masses
CRM Modal Optimization: Results
Best Found Point vs Iteration

Criterion: Point with best objective function AND sum of constraints
1. Tools
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5. Conclusion
6. Perspectives
What if the flow is not similar?

Reference aircraft: $r$

Scaled model: $m$

\[
\langle \bar{m}_r \rangle \{*_r \} + \langle \bar{m}_r \bar{\omega}_r^2 \rangle \{ \eta \} = \frac{1}{2} \frac{\mu_{1r}}{\kappa_{1r}^2} [\bar{a}_{hr}(X_{ar}, \kappa, M_r)] \{ \eta \}
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\]
What if the flow is not similar?

Reference aircraft: \( r \)

Scaled model: \( m \)

\[
\langle \tilde{m}_r \rangle \{ \eta \} + \langle \tilde{m}_r \bar{\omega}_r \rangle \{ \eta \} = \frac{1}{2} \frac{\mu_{1r}}{\sigma_{1r}^2} \left[ \tilde{a}_{hr}(X_{ar}, \kappa, M_r) \right] \{ \eta \}
\]

matched through modal optimization

\[
\langle \tilde{m}_m \rangle \{ \eta \} + \langle \tilde{m}_m \bar{\omega}_m \rangle \{ \eta \} = \frac{1}{2} \frac{\mu_{1m}}{\sigma_{1m}^2} \left[ \tilde{a}_{hm}(X_{am}, \kappa, M_m) \right] \{ \eta \}
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\]

optimize w.r.t. \( X_{am} \)
What if the flow is not similar? Aerodynamic Optimization

- Reference aircraft: \( r \)
- Scale model: \( m \)
What if the flow is not similar? Aerodynamic Optimization

- Reference aircraft: \( r \)
- Scale model: \( m \)
- Reduced frequency: \( \kappa \)
- Mach number: \( M \)
What if the flow is not similar? Aerodynamic Optimization

- Reference aircraft: $r$
- Scale model: $m$
- Reduced frequency: $\kappa$
- Mach number: $M$

Objective function:
What if the flow is not similar? Aerodynamic Optimization

- Reference aircraft: $r$
- Scale model: $m$
- Reduced frequency: $\kappa$
- Mach number: $M$

Objective function:

$$f = \sum_i (||[\bar{a}_{hr}(X_{ar}, \kappa_i, M_r)] - [\bar{a}_{hm}(X_{am}, \kappa_i, M_m)]||)$$
What if the flow is not similar? Aerodynamic Optimization

- Reference aircraft: \( r \)
- Scale model: \( m \)
- Reduced frequency: \( \kappa \)
- Mach number: \( M \)

Objective function:

\[
f = \sum_{i} (\|\bar{a}_{hr}(X_{ar}, \kappa_i, M_r)) - \|\bar{a}_{hm}(X_{am}, \kappa_i, M_m)\|)
\]

Design variables:
What if the flow is not similar? Aerodynamic Optimization

- Reference aircraft: r
- Scale model: m
- Reduced frequency: $\kappa$
- Mach number: $M$

Objective function:

$$f = \sum_i \left( \| \tilde{a}_{hr}(X_{ar}, \kappa_i, M_r) \| - \| \tilde{a}_{hm}(X_{am}, \kappa_i, M_m) \| \right)$$

Design variables:

- $X_{am}$: Parameters defining the wing planform
Aerodynamic Optimization: Goland Wing Test Case

M=0.8 Baseline

M=0.3 Baseline
Aerodynamic Optimization: Goland Wing Test Case
1. Tools

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6. Perspectives
Review of the traditional dynamic aeroelastic scaling approach
Conclusion

- Review of the traditional dynamic aeroelastic scaling approach
- Modal optimization for similarity
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- Modal optimization for similarity
- Application to the CRM test case
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- Importance of no flow similarity
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- Application to the CRM test case
- Importance of no flow similarity
- Wing planform optimization for flutter similarity
1. Tools
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Perform flutter-based wing planform optimization with the CRM model
Perspectives

- Perform flutter-based wing planform optimization with the CRM model

- From the optimized planform, optimize wing twist distribution and structure properties to match static deflection
This work has been supported by the EU project 658570 - NextGen Airliners funded by Marie Skłodowska-Curie actions (MSCA).

Thanks for your attention!

Questions?